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Influences of Climate and Anthropogenic Disturbances on Wildfire Regimes of the Zuni Mountains, New Mexico, U.S.A.

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To the Graduate Council:

I am submitting herewith a thesis written by Monica Tyson Rother entitled "Influences of Climate and Anthropogenic Disturbances on Wildfire Regimes of the Zuni Mountains, New Mexico, U.S.A.." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.

Henri D. Grissino-Mayer, Major Professor

We have read this thesis and recommend its acceptance:

Sally P. Horn, Carol P. Harden

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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INFLUENCES OF CLIMATE AND ANTHROPOGENIC DISTURBANCES ON WILDFIRE REGIMES OF THE ZUNI MOUNTAINS, NEW MEXICO, U.S.A.

A Thesis Presented

for the Master of Science Degree

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Monica Tyson Rother

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ABSTRACT

This research examined the fire history of ponderosa pine (*Pinus ponderosa* Douglas ex P. Lawson & C. Lawson) forests in northwestern New Mexico. The study area included three sites in the Zuni Mountains of Cibola National Forest and one site along the boundary of El Malpais National Monument. I crossdated over 800 fire scars on 75 samples to reconstruct spatial and temporal characteristics of historic wildfire regimes. The Weibull Median Interval, Weibull Modal Interval, and Mean Fire Interval ranged from five to eight years across all sites and percent-scarred classes (all fires, 10% scarred, and 25% scarred) and indicated that low-severity wildfires occurred frequently in the study area during the period 1700 to 1880.

Wildfires were historically driven by climatic variability. Superposed Epoch Analyses revealed that wetter conditions typically occurred one to three years prior to a fire event and were followed by drought during the fire year. No relationship was found between the Pacific Decadal Oscillation (PDO) and wildfire occurrence. These findings implied that shorter-term fluxes between wet and dry conditions, rather than longer-term climatic variability, were historically most conducive to fire occurrence. Fire frequency decreased suddenly in the late 19th century across the study area, and results indicated that fire has been absent at all sites since the 1920s. Anthropogenic disturbances including livestock grazing, timber harvesting, and fire suppression likely explain observed differences between historic and contemporary wildfire regimes in the Zuni Mountains.

This research has important implications for forest management. In ponderosa pine forests of the southwestern United States, land managers often aim to restore historic ecological conditions. The reintroduction of a frequent, low-severity wildfire regime might restore some

ecological patterns and processes, but given the strong legacy of human disturbances and the influences of human-induced climate change, a complete return to historic conditions may be neither possible nor desired.

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CHAPTER ONE

1. INTRODUCTION AND OBJECTIVES

1.1 Introduction

In recent decades, research has challenged the conventional idea that wildfires are unnatural and destructive. Evidence indicates that wildfire historically behaved as a natural disturbance in nearly all terrestrial ecosystems (Agee 1998; Dellasala *et al.* 2004; Pausas and Keeley 2009), and that fire exclusion has inhibited the important ecological roles of fire in many forests (Cooper 1960; Covington and Moore 1994; Allen *et al.* 2002). In ponderosa pine (*Pinus ponderosa* Douglas ex P. Lawson & C. Lawson) forests of the southwestern United States, land managers now aim to reintroduce a frequent, low-severity wildfire regime. However, this goal is difficult to achieve because of a strong legacy of past anthropogenic disturbances, which have heavily altered ecosystem patterns and processes. Moreover, research suggests that human-induced climate change may be further disrupting ecosystem functioning (Grissino-Mayer *et al.* 2004; Westerling *et al*. 2006; Brown 2006; Heyerdahl *et al.* 2008; Flannigan *et al.* 2009). It is thus imperative that decisions regarding land management in southwestern ponderosa pine forests be made with consideration of both the complex history and future trajectory of these forests.

An understanding of historic wildfire regimes requires examination of fire-climate relationships. Earlier research in the Southwest focused on how short-term climatic conditions such as annual drought influenced fire occurrence. Drought conditions were found to increase fire activity in the same year (Dietrich 1983; Swetnam and Baisan 1996). Researchers also examined the role of the El Niño-Southern Oscillation (ENSO), and observed that in the

Southwest, positive (El Niño) phases were associated with wetter conditions and reduced fire activity, while the opposite conditions (drier climate, increased fire activity) were associated with negative (La Niña) phases (Swetnam and Betancourt 1990; Westerling and Swetnam 2003). More recently, researchers have also been examining how decadal to multidecadal climatic variability can influence fire occurrence (Schoennagel *et al.* 2005, 2007; Brown 2006; Kitzberger *et al.* 2007; Heyerdahl *et al*. 2008). I followed this trend and assessed how both short-term and long-term climatic variability influenced fire activity in the Zuni Mountains, New Mexico. An understanding of these relationships might allow researchers to make better inferences regarding future fire behavior.

The relationship between climate and wildfire was disrupted in southwestern ponderosa pine forests around the time of Euro-American settlement in the late 19th century. In most cases, the first human-related change in fire frequency occurred *ca.* 1880 with the advent of livestock grazing. Herbivory by sheep and cattle removed fine fuels necessary for fire spread and rapidly reduced fire frequency (Leopold 1924; Cooper 1960; Savage and Swetnam 1990; Touchan *et al.* 1995; Grissino-Mayer and Swetnam 1997). A few decades later, timber harvesting further altered wildfire regimes by promoting the establishment of young pines and thus ultimately increasing stand density (Covington 2003). Finally, widespread and effective fire suppression efforts beginning in the 1940s exasperated the effects of earlier anthropogenic disturbances and virtually eliminated wildfire occurrence. The resulting ecological conditions are associated with an increased risk of high-severity wildfire (Cooper 1960; Covington and Moore 1994; Grissino-Mayer and Swetnam 1997; Allen *et al.* 2002). Given the known history of land-use change in the southwestern United States, my analysis of climate-fire relationships and of historic fire frequency focused on a period prior to major anthropogenic disturbances (1700–1880).

1.2 Research objectives and questions

This research examined the historic influences of climatic variability and land-use change on wildfire regimes of the Zuni Mountains, New Mexico. I relied on dendroecological methods to reconstruct wildfire regimes from fire scars. Climate-fire relationships were analyzed using Superposed Epoch Analyses for the period 1700 to 1880, prior to significant anthropogenic disturbances. I examined the decline in fire frequency that began *ca.* 1880, and considered the roles that land-use changes including livestock grazing, timber harvesting, and fire suppression might have played in leading to this decline. The specific research objectives and accompanying research questions of this thesis were as follows:

(1) *Characterize historic* (1700–1880) *wildfire regimes*.

Q. How can historic wildfire regimes of the Zuni Mountains be described in terms of fire frequency, severity, and extent?

(2) *Determine the influence of anthropogenic disturbances on wildfire regimes*.

Q. What role did anthropogenic disturbances such as livestock grazing, timber harvesting, and fire suppression play in altering wildfire regimes?

(3) *Examine historic (1700–1880) climate-wildfire relationships*.

Q. What was the historic relationship between short-term climatic patterns such as annual precipitation and wildfire occurrence?

Q. Did longer-term variability in ENSO and in the Pacific Decadal Oscillation (PDO) affect wildfire activity?

(4) *Compare wildfire regimes of each of the four sites in the Zuni Mountains in terms of fire frequency and synchrony. Also compare wildfire regimes of the Zuni Mountains to those of the adjacent El Malpais National Monument.*

Q. Were historic (1700–1880) fire regimes similar across the Zuni Mountains?

Q. How did historic fire regimes of the Zuni Mountains compare to those of El Malpais National Monument?

Q. Did fires in the Zuni Mountains occur synchronously with fires in El Malpais National Monument?

(5) *Make inferences about climate-wildfire relationships and overall forest health in the face of climate change.*

Q. What are the implications of historic (1700–1880) climate-wildfire relationships for the future given human-induced climate change and the legacy of anthropogenic disturbances?

Q. How might human-induced climate change affect forest health and wildfire behavior in the Zuni Mountains and throughout the Southwest?

(6) *Make suggestions for land managers in the Zuni Mountain area and throughout the Southwest.*

Q. What are the implications of this research for land management?

Q. Is complete restoration possible given current ecological conditions and predictions of continued climate change?

1.3 Dendrochronology

1.3.1 A brief history of dendrochronology

Dendrochronology is the science that analyzes information recorded in annually formed tree rings (Grissino-Mayer 2010). The understanding that a tree ring develops each year is ancient and extends back to the time of Theophrastus of Greece (370–285 B.C.). Theophrastus studied under Aristotle and was the earliest to articulate in writing the idea that new wood is added circumferentially to the outside of a tree (Studhalter 1956). Other early figures in dendrochronology included Leonardo da Vinci, Henri Louis Duhamel du Monceau, Charles Babbage, Theodor Hartig, and Robert Hartig (Baillie 1982; Speer 2010). These individuals understood annual ring formation and suggested a relationship between climate and ring width, but did not use modern methods to date annual rings. In the 1920s, A.E. Douglass pioneered the method of crossdating, a technique still used by dendrochronologists to accurately date tree rings. Douglass applied crossdating to his archaeological research in the American Southwest. He dated rings in wood found in ancient pueblos against rings in living and dead material from trees in the surrounding area to determine the construction dates of structures at nearly 40 archaeological sites (Douglass 1929).

Following the pioneering work of A.E. Douglass, dendrochronologists began to apply tree rings to increasingly diverse applications. These applications included climate reconstructions (*e.g.* Schulman 1956; Fritts 1971), the dating of geologic events such as volcanic eruptions (*e.g.* Yamaguchi 1983), studies of insect outbreaks (*e.g.* Blais 1962; Swetnam and Lynch 1993; Eisenhart and Veblen 2000), and analyses of how air pollution can affect tree growth (*e.g.* Ashby and Fritts 1972; Baes III and McLaughlin 1984). The science of dendrochronology is relatively young and continues to develop. Recent frontiers include the analysis of disturbance interactions, tropical dendrochronology, the linkage of tree rings to other proxies, and stable isotope analyses (Speer 2010).

1.3.2 Principles of dendrochronology

Dendrochronology is based on a set of key principles (Grissino-Mayer 2010). The principle of uniformitarianism is important to many fields of science and was first proposed by the geologist James Hutton in the late 18th century. Most simply stated, this principle holds that "the present is the key to the past." In the context of dendrochronology, uniformitarianism implies that biological and physical processes that presently determine patterns of tree growth also applied in the past (Fritts 1976; Speer 2010; Grissino-Mayer 2010). In addition, dendrochronologists can use their understanding of past patterns and processes to make inferences about the future (Grissino-Mayer 2010). Although the principle of uniformitarianism continues to be central to tree-ring science, researchers have recently noted that climate/tree-growth relationships can be unstable over time (Briffa *et al.* 1998; Driscoll *et al.* 2005; Biermann 2009). This instability challenges uniformitarianism and is termed "the divergence problem." The divergence problem does not invalidate dendroclimatic studies, but it does imply that scientists should test assumptions regarding stability in the climate/tree-growth record before reconstructing climate (Biondi and Waikul 2004; Biermann 2009).

The principle of crossdating describes how dendrochronologists date annual tree rings. Crossdating allows researchers not only to date rings in living trees, but also to extend tree-ring chronologies back in time by including specimens from dead trees and/or archaeological specimens. Simple ring counts are inappropriate for most dendrochronological applications because locally absent and/or false rings can lead to erroneous dating. The earliest and most foundational method of crossdating was developed by A.E. Douglass and is known as skeleton plotting. Patterns of narrow and wide rings on a tree series are graphed and are then compared to a reference chronology (Stokes and Smiley 1968). Other visual methods of crossdating include the list method and the memorization method, although these approaches require more familiarity with the master chronology (Speer 2010).

The principle of aggregate tree growth and the principle of limiting factors are complementary and explain drivers of tree growth. According to the principle of aggregate tree growth, numerous factors may account for variability in ring width from year to year. The equation that describes this variability is: $R_t = A_t + C_t + \delta D1_t + \delta D2_t + E_t$. Thus tree-ring growth (R) in any given year (t) is a function of the age-related growth trend (A), climate (C), endogenous (D_1) and exogenous (D_2) disturbances, and a certain amount of error (E) not accounted for by the other variables (Grissino-Mayer 2010). While the principle of aggregate tree growth suggests that numerous factors influence ring formation, the principle of limiting factors holds that the single most limiting environmental factor will ultimately control tree growth (Grissino-Mayer 2010; Speer 2010).

The principle of site selection and the principle of ecological amplitude are also complementary and help dendrochronologists choose appropriate locations for tree-ring studies. Dendrochronologists typically desire "sensitive" tree-ring series that show a high degree of variability in ring width from year to year. According to the principle of site selection, researchers should choose locations where the tree species of interest is most responsive to the environmental variable of concern. For example, a dendrochronologist interested in the relationship between drought and tree growth should collect samples from an area where tree growth is limited by precipitation (Stokes and Smiley 1968; Fritts 1976; Grissino-Mayer 2010; Speer 2010). The principle of ecological amplitude also addresses site selection and is based on the observation that trees tend to be most sensitive towards the edges of their range (Fritts 1976; Grissino-Mayer 2010; Speer 2010).

Finally, the principle of replication states that repeated sampling should be integrated into any dendrochronological study. Researchers should sample more than one stem radius per tree, and should also sample numerous trees per site. If addressing questions at a broad spatial scale, multiple sites should be established across a large area. These strategies reduce the undesired "noise" recorded by an individual tree, and maximize the amount of desired "signal" (Stokes and Smiley 1968; Fritts 1976; Speer 2010; Grissino-Mayer 2010).

1.3.3 Dendropyrochronology

My research relied primarily on dendropyrochronology, the subfield of dendrochronology used to characterize past fire regimes. Researchers acknowledge that ecosystems are dynamic, and so aim to determine the historic range of variability of fire characteristics such as frequency, severity and extent (Landres *et al.* 1999; Veblen and Donnegan 2006). In the Southwest, dendropyrochronological studies have reconstructed the occurrence of low-severity wildfires by dating fire scars recorded in annual rings (Arno and Sneck 1977; Dieterich and Swetnam 1984; Swetnam and Baisan 1996; Grissino-Mayer and Swetnam 1997). Dates of fire scars are compiled to build chronologies from multiple trees. Analysis of these chronologies facilitates understanding of the spatial and temporal characteristics of historic wildfire regimes at one site.

Similarly, comparison among chronologies allows researchers to identify patterns at larger spatial scales (Arno and Sneck 1977; Dieterich and Swetnam 1984; Swetnam and Baisan 1996; Swetnam and Baisan 2003). Ponderosa pine forests of the southwestern United States lend themselves well to fire-history studies because ponderosa pine survives low-intensity fire and often scars repeatedly (Dieterich and Swetnam 1984).

1.4 Organization of thesis

This thesis is divided into seven chapters. This first chapter introduces and justifies my research. An explanation of the questions and objectives for this study is followed by a brief overview of dendrochronology. Chapter Two is a literature review that summarizes relevant previous research. Chapter Three describes the study area. The geology, climate, vegetation, and land-use history of the entire study area are described, followed by detailed descriptions of the four study sites. Chapter Four presents the field and laboratory methods used in this research. Results are then presented and discussed in Chapters Five and Six. Finally, in Chapter Seven, the thesis is concluded and suggestions are made regarding directions for future research.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 The relationship between land-use change and wildfire in the Southwest

The relationship between land-use change and wildfire activity has been well documented in the southwestern United States (Cooper 1960; White 1985; Covington and Moore 1994; Allen *et al.* 2002). Previous research indicated that fire frequency decreased in the late 19th century (*ca.* 1880) with the advent of livestock grazing. Herbivory by sheep and cattle reduced fire frequency and extent by removing fine fuels necessary for fire spread. The timing of this anthropogenic disturbance varied by site, and some areas were completely isolated from grazing (Savage and Swetnam 1990; Grissino-Mayer and Swetnam 1997; Touchan *et al.* 1995; Lewis 2003). Fire-history studies from the Southwest have also noted the relationship between fire suppression and fire frequency in the early 20th century. Fire suppression efforts further excluded wildfire and facilitated additional changes in forest composition and structure (Cooper 1960; Savage and Swetnam 1990; Covington and Moore 1994; Grissino-Mayer and Swetnam 1997; Allen *et al.* 2002).

2.1.1 Fire histories of ponderosa pine forests in New Mexico by Touchan et al. (1995)

In 1995, Touchan *et al.* reconstructed the fire histories of three ponderosa pine forests in northern New Mexico. They argued that the unique grazing histories of each forest largely explained dissimilarities in fire regimes. At a site in Monument Canyon Natural Area, fire frequency decreased around 1899 with the advent of sheepherding. In contrast, the Continental

Divide site experienced a decline in fire frequency much earlier, beginning in the 1750s as a consequence of grazing by Navajo and Hispanic populations. Sheepherding did not appear to affect the third site on kipukas in El Malpais National Monument, as little variation in fire frequency occurred in the 19th and 20th centuries. The rugged lava surrounding the kipukas likely provided protection from grazing. Touchan *et al.* used their findings to make several generalizations about their study area and the entire Southwest. They concluded that livestock grazing was the initial and most significant cause of decreased fire frequency. Later, reduced grazing, changes in climate, and fire suppression facilitated the establishment and survival of many young trees and led to the development of dense even-aged stands. Touchan *et al.* stressed that the timing and extent of anthropogenic disturbances varied spatially, and suggested that this variability be taken into account when making land-management decisions that aim to restore pre-settlement wildfire regimes.

2.1.2 Fire history of El Malpais National Monument by Grissino-Mayer and Swetnam (1997)

Grissino-Mayer and Swetnam (1997) reconstructed a multicentury fire history of ponderosa pine forests in El Malpais National Monument. They determined reference conditions for fire behavior prior to Euro-American settlement. They sampled on cinder cones and shield volcanoes, ancient eroded basalt flows, younger basalt flows, and isolated kipukas. In all, they analyzed specimens from 217 trees, and dated over 3,000 fires scars. Their findings regarding land-use change and fire behavior complemented those of Touchan *et al.* (1995). Grissino-Mayer and Swetnam found that prior to Euro-American settlement, low-intensity surface fires occurred frequently and helped maintain open park-like conditions. Fire frequency decreased suddenly around 1880, a change that they associated with the advent of widespread sheepherding. Then, around 1940, fire frequency further decreased with the introduction of more effective fire suppression methods such as smoke jumping. In the absence of fire, dense “doghair” thickets of young ponderosa pine replaced open stands. These forest conditions promote high-severity wildfires atypical of the pre-settlement fire regimes. Although similar patterns emerged across the study area, Grissino-Mayer and Swetnam emphasized that different habitat types were characterized by unique fire histories. For example, fires occurred less frequently on the kipukas than at the cinder-cone/shield-volcano sites. They suggested that customized fire management strategies should be applied to restore reference conditions to the diverse habitat types within the National Monument.

2.1.3 Fire history of kipukas in El Malpais National Monument by Lewis (2003)

In 2003, Lewis completed an M.S. thesis on the fire histories of forested kipukas in El Malpais National Monument. Lewis established eight sites and collected a total of 105 fire-scarred cross sections, mostly from ponderosa pine. Five sites were on kipukas and three were on surrounding lava flows. Lewis also collected increment cores from living ponderosa pines on two of the kipukas. He used the cores to analyze age structure and to determine whether or not fire suppression on the surrounding lava flows had affected fire behavior on the kipukas. Fire-history analyses revealed similar patterns across the study area. Lewis determined that fire historically occurred frequently both on and off the kipukas. When he combined the fire histories from all eight sites, he determined the Mean Fire Interval, Weibull Median Interval, and Weibull Modal Interval to be 5.9, 5.3, and 3.7 years, respectively, for the all-fires class. Throughout the National

Monument, Lewis observed that fire essentially ceased around 1933. The age structure analysis of the kipukas helped explain this pattern and revealed that a large cohort of ponderosa pines had established together less than 100 years B.P., likely as a consequence of fire exclusion on the surrounding lava flows. Collectively, the work of Touchan *et al.* (1995), Grissino-Mayer and Swetnam (1997), and Lewis (2003) indicated that low-severity fires occurred frequently in southwestern forests until disruption by various land-use changes.

2.2 Climate-fire relationships in the Southwest

Climate-fire studies in the southwestern United States have focused on how short-term climatic variability has driven wildfire occurrence. For example, correlation analysis has been used to assess the annual relationship between ENSO events and fire occurrence. Positive ENSO phases were associated with wetter conditions and reduced fire activity, while the opposite conditions (drier climate, increased fire activity) were associated with negative ENSO phases (Swetnam and Betancourt 1990). Researchers have also examined the interannual relationships between fire and climate. Through use of Superposed Epoch Analysis, researchers have observed a lagging effect in historic climate-fire relationships. Fires often occurred following a switch from relatively wet conditions one to three years prior to fire, to dry conditions during the fire year (Swetnam and Baisan 1996; Grissino-Mayer and Swetnam 2000).

2.2.1 ENSO and wildfire activity by Swetnam and Betancourt (1990)

Swetnam and Betancourt (1990) examined the annual relationship between ENSO and wildfire occurrence in the southwestern United States. They coupled fire-scar and tree-growth chronologies with fire statistics of area burned to examine fire-climate relationships in New Mexico and Arizona from 1700 to 1985. They found that warm phase ENSO years (*i.e.* El Niño years) generally resulted in significantly wetter spring seasons, and that these wetter springs corresponded with relatively small areas burned. In contrast, cool phase ENSO years (*i.e.* La Niña years) coincided with drier springs and larger areas burned. Severe fire years often occurred synchronously in many southwestern forests, demonstrating the broadscale influence of variability in ENSO.

2.2.2 Long-term rainfall trends and wildfire by Grissino-Mayer and Swetnam (2000)

Grissino-Mayer and Swetnam (2000) further analyzed the historic relationship between climate and wildfire in the Southwest. They compared their fire-history results from northwestern New Mexico to a dendroclimatic rainfall reconstruction that had been developed for the region several years earlier (Grissino-Mayer 1995, 1996). They observed that a long, dry period with high fire frequency occurred from 1400 to 1790. After 1790, precipitation increased and fire frequency decreased. Superposed Epoch Analysis revealed that during the earlier period (1400–1790), fire often occurred during severe drought years. In contrast, after 1790, a lagging effect was apparent where above normal precipitation occurred three years prior to a fire event and was followed by drought in the fire year. Antecedent moister conditions increased fuel availability, while drought during the fire year desiccated fuels for burning. Thus while Swetnam and Betancourt (1990) observed annual linkages between ENSO and wildfire, Grissino-Mayer and Swetnam (2000) demonstrated that interannual patterns also occurred. These interannual trends can vary over time as global-scale atmospheric/oceanic circulation patterns change.

2.3 Long-term climate trends and climate-wildfire relationships throughout the United States

Fire-climate research has increasingly examined how long-term oceanic-atmospheric circulation features influence drought and fire behavior (McCabe *et al.* 2004; Brown 2006; Kitzberger *et al.* 2007; Schoennagel *et al.* 2005, 2007; Heyerdahl *et al.* 2008). In North America, the relationship between ENSO, PDO, the Atlantic Multidecadal Oscillation (AMO), and wildfire behavior has been of particular interest. These three long-term climatic patterns were discovered and described relatively recently (*see* Mantua *et al.* 1997; Diaz and Markgraf 2000; Kerr 2000) and so exploration of their relationship to wildfire is incomplete and ongoing.

2.3.1 PDO, AMO and drought frequency in the United States by McCabe et al. (2004)

McCabe *et al.* (2004) examined the relationships between AMO, PDO and drought frequency in the United States. They determined that approximately half of the spatial and temporal variance in multidecadal drought frequency in the contiguous United States could be explained by PDO and AMO. A positive phase of AMO corresponded with widespread drought conditions throughout most of the country. Historically, when a positive AMO phase occurred during a negative PDO phase, drought conditions prevailed in the Midwest, Southwest, and Rocky Mountain/Great Basin area. This type of drought occurred in the 1950s. A different drought situation developed when a positive AMO combined with a positive PDO, such as occurred in the 1930s. In this case, the Southwest remained relatively wet while the northern two-thirds of the United States experienced drought conditions. McCabe *et al.* argued that in the upcoming decade, the AMO is likely to persist in a positive phase and, as a consequence, future drought is probable. Whether upcoming drought will be most similar to that of the 1930s or that of the 1950s will depend on whether the PDO is positive or negative.

2.3.2 ENSO, PDO, AMO and wildfire in the Black Hills by Brown (2006)

While McCabe *et al.* (2004) focused specifically on how PDO and AMO affected drought, Brown (2006) looked for a connection between broadscale climatic patterns (PDO, AMO, and ENSO) and wildfire. He focused specifically on ponderosa pine forests of the Black Hills of southwestern South Dakota and northeastern Wyoming. He used Superposed Epoch Analyses to examine wildfire-climate relationships by comparing regional fire years to reconstructions of precipitation, ENSO, PDO, and AMO. In keeping with earlier findings for the Southwest (*e.g.* Swetnam and Betancourt 1990), Brown observed that regional fire years occurred most frequently during negative phases of ENSO (La Niña). He also found that when a negative ENSO phase aligned with a negative phase of PDO and a positive phase of AMO, fire frequency further increased. In contrast, fewer fires occurred during the opposite phase combination (positive ENSO, positive PDO, negative AMO).

2.3.3 ENSO, PDO, AMO and wildfire in western Colorado by Schoennagel et al. (2007)

Schoennagel *et al.* (2007) also investigated the relationships between broadscale climatic patterns and wildfire occurrence. They examined how decadal to multidecadal climatic variability associated with ENSO, PDO, and AMO affected fire behavior in subalpine forests of western Colorado. Stand-replacing fire is a primary disturbance agent in these forests, and thus a combination of fire-history methods was required to reconstruct fire occurrence. Fire dates from fire-scarred trees were coupled with stand-origin dates from adjacent or nearby stands.

After reconstructing fire history, Schoennagel *et al.* conducted fire-climate analyses on the period 1600 to 2003. They examined interannual relationships between climate and fire using Superposed Epoch Analysis, in keeping with previous studies. Longer-term relationships were examined using a new method, Bivariate Event Analysis (D.G. Gavin, *unpublished software*). Schoennagel *et al.* observed many patterns through their analyses. Perhaps most significantly, they determined that a combination of a positive AMO, negative ENSO, and negative PDO created "triple whammies," during which the probability of fire induced by drought increased substantially. These results are in agreement with those of Brown (2006) and suggest that climate-wildfire relationships related to ENSO, PDO, and AMO can apply across broadscale areas of the United States.

2.3.4 PDO, ENSO, AMO and wildfire in western North America by Kitzberger et al. (2007)

To test climate-fire relationships across a large spatial scale, Kitzberger *et al.* (2007) examined relationships between ENSO, PDO, AMO, and wildfire across western North America. Their broadscale study included 33,039 fire-scar dates from 238 sites in Mexico, the United States, and Canada. They used rotated principal components analysis and determined that since *ca.* 1550, wildfires across the West were most commonly synchronous during positive phases of AMO. The relationship between PDO, ENSO and wildfire varied by subregion, and fire synchrony was inconsistent. While earlier research (McCabe *et al.* 2004) suggested that a positive AMO phase would bring future long-term drought throughout much of the United

States, Kitzberger *et al.* added that a positive AMO phase might also result in increased widespread, synchronous wildfires across the western United States.

2.4 Wildfire in the face of climate change

Forecasting wildfire in the face of human-induced climate change is difficult because many variables affect wildfire occurrence. In the American Southwest, land-use changes have altered forest composition and structure outside historic ranges of variability (Cooper 1960; Covington and Moore 1994; Grissino-Mayer and Swetnam 1997; Allen *et al.* 2002). Although past relationships between wet/dry lagging patterns and wildfire have been well established (Baisan and Swetnam 1990; Swetnam and Betancourt 1998; Grissino-Mayer and Swetnam 2000; Grissino-Mayer *et al.* 2004; Sherriff and Veblen 2008), anthropogenic disturbances have disrupted these relationships. In addition, some uncertainty still surrounds the magnitude of anticipated changes in temperature and precipitation, and how these changes will vary spatially across the United States (IPCC 2007).

2.4.1 Changing climate drives increased wildfire by Westerling et al. (2006)

Westerling *et al.* (2006) compiled a comprehensive time series of recent, large (> 400 ha) wildfires in the western United States. The times series included 1166 fires that occurred from 1970 to 2003 on federal land-management units. They compared these data to various hydroclimatic and land surface variables to determine where changes in fire activity were occurring, and what factors might be driving those changes. They approached their analysis with the assumption that climatic variability, rather than land-use change, served as the primary driver of fire in the western United States.

Westerling *et al.* observed abrupt changes in wildfire beginning in the mid-1980s. Wildfires increased in size and duration, burning larger areas for greater periods of time. After 1986, wildfire frequency was almost four times the average frequency for the period 1970 to 1986. These changes coincided with a transition towards increased spring and summer temperatures and an earlier spring snowmelt. The greatest increase in large wildfire occurrence took place in forests of the Northern Rockies. An increase was also observed in the Southwest, an area heavily impacted by fire exclusion. However, in the Southwest, changes in the timing of spring appeared to be less important. Westerling *et al.* used their findings to make suggestions about future forest management, arguing that ecological restoration and fire management practices might not sufficiently moderate increased wildfire activity driven primarily by climate change.

2.4.2 Future wildfire synchrony and severity by Heyerdahl et al. (2008)

Heyerdahl *et al.* (2008) examined climate-fire relationships in portions of the northern Rockies of Idaho and western Montana. They observed that during the period of analysis (1650–1900), regionally synchronous fires occurred frequently across their study area. These fires often occurred when spring–summers were warm and summers were both warm and dry. Heyerdahl *et al.* argued that although many forests have been heavily affected by land-use change, climate continues to drive regional wildfire synchrony. Given that model predictions of greenhouse gas and aerosol induced climate change have predicted an even earlier melting of snowpack, Heyerdahl *et al.* suggested that fire synchrony across the West might further increase.

2.5 Summary of main conclusions from previous research

- Throughout much of the Southwest, livestock grazing reduced fire frequency *ca.* 1880. Later, fire suppression led by the U.S. Forest Service further excluded fire occurrence (Grissino-Mayer and Swetnam 1997; Touchan *et al.* 1995; Lewis 2003).
- Wildfire in the Southwest was historically driven by changes in precipitation patterns. ENSO affects rainfall variability and thus promoted or inhibited wildfire (Swetnam and Betancourt 1990; Grissino-Mayer and Swetnam 2000).
- In many parts of the United States, long-term climatic patterns including PDO and AMO were associated with changes in fire behavior. Certain phase combinations of ENSO, PDO, and AMO corresponded with increased wildfire frequency, severity, and synchrony (Brown 2006; Schoennagel *et al.* 2007; Kitzberger *et al.* 2007).
- The frequency of severe and synchronous wildfires in the United States might further increase in response to human-induced climate change (Westerling *et al.* 2006; Heyerdahl *et al.* 2008).

CHAPTER THREE

3. SETTING

3.1 Geology and soils

The study area is situated in the Zuni Mountains along the southeastern edge of the Colorado Plateau. Although most mountains in this region are of volcanic origin, the Zunis resulted from geologic uplift (Chronic 1987; Julyan 2006). They form a broad dome trending northwest-southeast and are approximately 85 km long and 35 km wide. The core of the Zunis consists of Precambrian granite and metamorphic rock that was originally covered by a thick layer of sedimentary rock from the Cretaceous and earlier periods. This sedimentary rock once arched over the entire mountain chain, but was eroded away as the mountains uplifted (Chronic 1987). Current elevations throughout the Zunis range from a low of approximately 2,000 m at the foothills, to a maximum of 2,820 m at Mount Sedgwick. The southeastern edge of the mountains is adjacent to the northern boundary of El Malpais National Monument, an area characterized by geologically young lava flows (Lindsey 1951). Although evidence of past volcanic activity is less prominent in the Zunis than in the National Monument, volcanic cinder cones and associated basaltic lava flows do occur (Robinson 1994).

Soils of northwestern New Mexico are most often classified as Aridisols, Entisols, and Alfisols, although Inceptisols, Vertisols, and Mollisols also occur (Francis and Aguilar 1995). Unlike those in the National Monument, soils in the Zunis are typically well developed and are of sedimentary and/or metamorphic origin. In some areas, including on and around Paxton Springs Cinder Cone, soils are of volcanic origin and are thin, rocky, and poorly developed. Throughout high mountainous regions in New Mexico, soils are leached, acidic, and nutrient poor due to the relatively wet, cool climate and the dominance of coniferous trees (Dick-Peddie 1993). Nutrient availability in the soil is also low because historic fire exclusion practices such as livestock grazing and fire suppression prevented nutrient cycling (Covington and Sackett 1992; Selmants *et al.* 2003).

3.2 Climate

3.2.1 Temperature

Mean annual temperature in New Mexico is approximately 12 ºC, with large seasonal differences between summer and winter temperatures (Sheppard *et al.* 2002) (Figure 3.1). Data from the National Climate Data Center indicate that temperatures are lowest in December and January and then peak in July. High summer temperatures occur in part because incoming solar insolation is expended to heat the land surface, rather than to evaporate soil moisture as occurs in wetter areas. Temperatures vary with elevation, and mountainous regions such as the Zunis are notably cooler. Extreme temperatures can occur; a record low of –45 °C was recorded on February 1, 1951, in northwestern New Mexico, and a record high of 53 °C occurred in west central Arizona on June 29, 1994 (Sheppard *et al.* 2002).

In the Southwest and throughout the United States, human-induced climate change may be driving temperatures above the historic range of variability. Of the 12 warmest years in the instrumental record, 11 occurred between 1995 and 2006 (IPCC 2007). However, there remains uncertainty as to whether or not these temperatures are anomalous given a coarser temporal scale. A well-known study by Mann *et al.* (1998) addressed this topic through a reconstruction of Northern Hemisphere temperature from a large network of proxy data. The reconstruction relied

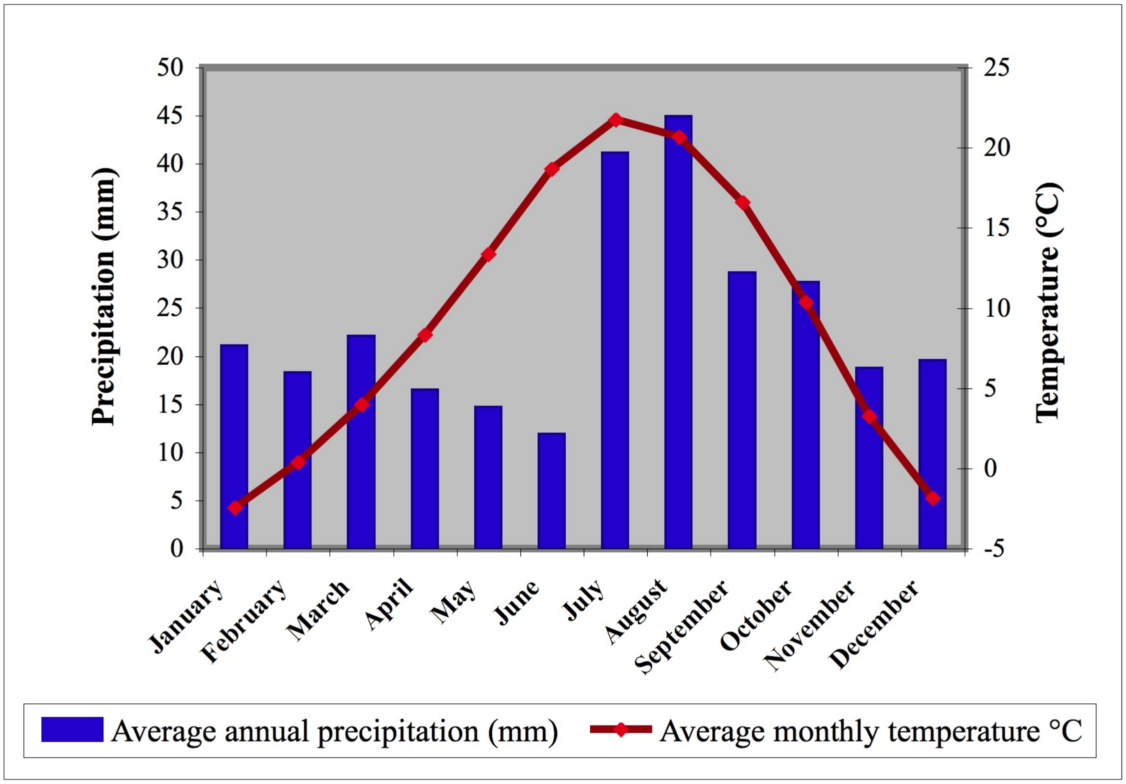

Figure 3.1 Annual precipitation and temperature patterns from National Climatic Data Center Division One data for New Mexico.

most heavily on tree-ring data, but also included historical records and ice core, ice melt, and coral data. Mann *et al.* concluded that temperatures in the 1990s were the warmest since A.D. 1000. Reconstructed temperatures were relatively low for hundreds of years and then spiked rapidly at the end of the 20th century. Because of this unusual pattern, the reconstruction has been nicknamed the "hockey stick." Although the Mann *et al.* publication has recently fallen under significant criticism (*e.g.* McIntyre and McKitrick 2003; Essex and McKitrick 2007), the overwhelming scientific consensus remains that temperatures are on the rise and that these increases are associated with human-induced greenhouse gas emissions (IPCC 2007).

3.2.2 Precipitation

The Southwest experiences extremely low annual precipitation. Instrumental records from New Mexico indicate that average annual precipitation is around 340 mm (Figure 3.1). The aridity of the Southwest is largely a consequence of the semi-permanent positioning of the subtropical high-pressure ridge over the area (Sheppard *et al.* 2002). Most precipitation is in the form of rainfall, although at higher elevations, snowfall is common during winter months (Parham 1993). Mountainous areas also receive greater total precipitation due to orographic processes (Parham 1993; Sheppard *et al.* 2002). Precipitation is highly seasonal, with May through June drought typically followed by relatively wet conditions in July through September. These late summer months receive approximately 50% of annual rainfall and are followed by a second maximum from November through March that provides another 30% of annual rainfall (Sheppard *et al*. 2002).

The seasonality of southwestern precipitation is related to the North American Monsoon. Like all monsoons, the North American Monsoon is characterized by an abrupt seasonal change in wind direction of at least 120° (Sheppard *et al.* 2002). Each year, the North American Monsoon brings heavy rainfall and severe thunderstorms to the Southwest during summer months (Adams and Comrie 1997; Higgins *et al.* 1999; Sheppard *et al.* 2002; Crimmins 2006; Stahle *et al.* 2009). The effects of the monsoon are broadscale and are most noticeable in Arizona, New Mexico, and northwestern Mexico (Adams and Comrie 1997; Sheppard *et al.* 2002).

3.2.3 Lightning activity

The Southwest experiences extremely high lightning activity (Weaver 1951; Cooper 1960; Barrows 1978; Watson *et al.* 1994; Allen 2002; Barrett *et al.* 2005). Lightning activity peaks during the summer monsoon, when convectional thunderstorms and cloud-to-ground lightning strikes are most common (Barrows 1978; Watson *et al.* 1994; Allen 2002). Thunderstorms result when warm temperatures combine with moist maritime air, and are especially frequent over mountainous areas (Allen 2002). Krider *et al.* (1980) aimed to monitor lightning activity in Arizona and New Mexico in the summer of 1979, and detected over 8,000 flashes of lightning during only an 18-hour period. Krider *et al.* suggested that lightning activity be more carefully monitored in the Southwest as part of wildfire management practices. Although lightning activity typically peaks during the summer, lightning also occurs during the arid foresummer months, and poses an extreme fire hazard (Swetnam and Betancourt 1998; Allen 2002).

3.2.4 Broadscale climate oscillations

3.2.4.1 ENSO

ENSO is a two to ten year cycle of shifting sea surface temperature and pressure in the Pacific Ocean. Positive and negative ENSO events are referred to as El Niño and La Niña, respectively, and the intensity of each varies between cycles (Philander 1983; Sheppard *et al.* 2002). During an El Niño event, sea surface temperatures rise in the eastern equatorial Pacific and the active center of atmospheric convection shifts from the western to the central equatorial Pacific. In contrast, during la Niña years, sea surface temperatures drop in the eastern equatorial Pacific and atmospheric convection patterns remain relatively unchanged (Sheppard *et al.* 2002). Sir Charles Todd of Australia, who first observed climatic patterns related to ENSO in the late 1800s, noted that simultaneous drought in Australia and India coincided with high-pressure conditions (Nicholls 1992). Since then, researchers have clarified the mechanisms that drive ENSO and established its effect on interannual variability in climatic conditions at a global scale (Philander 1983).

In the southwestern United States, wetter than average fall–spring seasons correspond with positive (El Niño) phases while drier conditions occur during negative (La Niña) phases (Andrade Jr. and Sellers 1988; Swetnam and Betancourt 1990; D'Arrigo and Jacoby 1991; Westerling and Swetnam 2003). These ENSO-driven changes in precipitation help explain coincident variability in wildfire occurrence. For example, in some forests, wildfire was found to be particularly likely when several wet, El Niño years were followed by a dry, La Niña year (Baisan and Swetnam 1990; Swetnam and Betancourt 1998; Grissino-Mayer and Swetnam 2000; Grissino-Mayer *et al.* 2004; Sherriff and Veblen 2008).

3.2.4.2 PDO

The PDO occurs in 20 to 30 year cycles and results from variability in sea surface temperatures in the eastern Pacific Ocean. Fisheries scientist Steven Hare first coined the term "Pacific Decadal Oscillation" in reference to climate changes in the Pacific Ocean linked to variability in Alaskan salmon production cycles (Mantua *et al.* 1997). During positive PDO phases, sea surface temperatures increase in the eastern Pacific Ocean and sea surface temperatures decrease in the western and central North Pacific. During negative PDO phases, the opposite conditions occur. The effects of PDO on climate in the Southwest and throughout North America resemble those of ENSO but are less intense and are longer-lived (Mantua and Hare 2002; MacDonald and Case 2005). In the southwestern United States, a positive PDO phase coincides with increased precipitation, while a negative phase is associated with decreased precipitation (Mantua and Hare 2002). The relationship between PDO and wildfire in the Southwest remains uncertain, although Westerling and Swetnam (2003) suggested that when PDO synchronizes with ENSO (and both are positive or both are negative), ENSO conditions are intensified.

3.3 Ponderosa pine forests

3.3.1 Ponderosa pine

3.3.1.1 Distribution

Ponderosa pine is the most widely distributed species of *Pinus* in North America (Agee 1998). Its northernmost range extends through southern British Columbia and the species can be found as far south as Durango, Mexico. Along a longitudinal gradient, ponderosa pine is common throughout the western United States, excluding the Great Basin area (USDA 1965; Mirov 1967; Little 1971). The species existed in North America at least as early as 600,000 years B.P., as shown by fossil remains found in west central Nevada (Moir *et al.* 1997). Climate largely controls the range of ponderosa pine (USDA 1965), and long-term climatic changes have altered its distribution. For example, Betancourt (1990) used packrat (*Neotoma* spp.) middens to reconstruct the late Quaternary biogeography of the Colorado Plateau and found that ponderosa pine was absent from the midden record during the Wisconsin period (approximately 11–65 ka) when temperatures were cooler. Ponderosa pine then rapidly expanded and gained its modern distribution as temperatures warmed in the late Holocene.

3.3.1.2 Life history and adaptations

Ponderosa pine may occur as a seral or climax species. In xerophytic forests, such as those in the American Southwest, the tree reproduces successfully in mid- to late succession and is thus considered a climax species (Moir *et al.* 1997). Ponderosa pine is long-lived and the oldest individual tree ever dated was 929 years old (Brown 2010). Trees typically reach maturity after 70 to 250 years. With age, bark becomes increasingly plated and changes color from a brownish-black to a reddish-brown or orange-yellow color. Mature trees range in height from 17 to 27 m, and diameter at breast height ranges from 38 to 89 cm. Needles are typically in clusters of three, although two- and four- needle clusters also occur. Cones are 8 to 15 cm long and require two years to mature (USDA 2010).

Ponderosa pine thrives in a variety of ecological conditions. The species is drought resistant and is typically found where average annual temperatures range from 5 to 10 °C and where July to August temperatures are 17 to 21 °C (USDA 1965). Ponderosa pine is found on soils of igneous, metamorphic, and sedimentary origin (Schubert 1974). On shallow soils, trees will typically send out long lateral roots that serve to increase trunk stability and water uptake (USDA 1965).

Agee (1998) argued that the distribution and adaptations of the genus *Pinus* resulted in large part from its relationship with wildfire over both time and space. In the case of ponderosa pine, an obvious adaptation to wildfire is its exceptionally thick, corky bark. The bark is often 15 to 20 cm thick at chest height and serves to insulate the cambium against intense heat (Moir *et al.* 1997). The species also frequently sheds its needles, thereby providing fuels for frequent, low-severity wildfire (Arno and Allison-Bunnell 2002). Seeds are produced erratically, and wildfires promote successful establishment by clearing grasses and creating a mineral seedbed (White 1985). After a fire, injured trees will produce abundant pitch that seals off the damaged area and provides protection from disease (Arno and Allison-Bunnell 2002). The living portion of the cambium then grows over the injury. Ponderosa pines may scar repeatedly during their lifespan, as exemplified by a cross section from a 327 year-old tree in Arizona that contained 42 identifiable scars (Dieterich and Swetnam 1984). Although ponderosa pine is well adapted to wildfire, young trees may be susceptible to fire for the first several years after establishment. Wildfire in the same area in consecutive years can therefore inhibit regeneration because of this susceptibility (Cooper 1960).

3.3.2 Understory vegetation

Historically, the understory of southwestern ponderosa pine forests was herbaceous and included a variety of vascular plants such as shrubs, grasses, forbs, ferns, and cacti. Often, the most visible species were native bunchgrasses that grew in large clumps and included *Festuca arizonica* Vasey (Arizona fescue), *Muhlenbergia montana* Hitchc. (mountain muhly), *Poa fendleriana* Vasey (muttongrass), and *Elymus elymoides* (Raf.) Swezey (squirreltail) (Korb and Springer 2003). Although this type of understory still occurs, fire exclusion in the late 19th century and early 20th century altered stand dynamics in many southwestern ponderosa pine forests. Most notably, fire exclusion promoted the formation of a dense canopy that excluded light from reaching the forest floor and thus reduced the number and diversity of understory species (Moore and Deiter 1992; Korb and Springer 2003). This loss in understory diversity and density led to increased erosion rates, reduced soil nutrient levels, diminished habitat for wildlife, and increased establishment by pine seedlings (Pearson 1942; Korb and Springer 2003). Changes in the understory have affected wildfire regimes, as current ecological conditions are more conducive to high-severity wildfire (Cooper 1960; Covington and Moore 1994; Grissino-Mayer and Swetnam 1997; Allen *et al.* 2002).

3.3.3 Aspects of forest health

3.3.3.1 Land-use history

Livestock grazing altered ecological conditions in ponderosa pine forests of the Zuni Mountains. Sheepherding in particular was widespread in the late 19th and early 20th centuries. Sheep were raised in the nearby town of San Rafael, which was settled in 1869 following the subjugation of the Navajo people. The arrival of the Atlantic & Pacific Railroad in 1881 to the area facilitated large-scale operations, and by 1885, over 3.9 million sheep were grazing in New Mexico. This included many thousands of sheep based out of San Rafael. Cattle were also grazing the region beginning around 1880, but to a lesser degree than sheep (Magnum 1997). Livestock grazing remained profitable and widespread until the Great Depression (Robinson 1994; Magnum 1997).

Shortly after sheepherding began, forests of the Zuni Mountains were further altered by the timber industry. Logging operations started in 1890, when William and Austin Mitchell purchased more than 300,000 acres (121,000 hectares) of Zuni forest. The Zuni Mountain Railway was constructed out of a newly founded timber town, Mitchell to facilitate operations. This first attempt to log the Zunis was only moderately successful and was curtailed by economic difficulties. In the early 1900s, the American Lumber Company took over the Mitchell's land and was enormously productive (Magnum 1997; Myrick 1990). They expanded the railroad to include a line along Oso Ridge (Myrick 1990). At the height of business, around 1910, more than 700 individuals were employed as cutters in the Zunis, and in that year alone the company harvested over 60,000 board feet (142 m^3) of timber. Operations by the American Lumber Company ceased around 1913, but timber harvesting continued over the next several decades. It was not until the 1940s that economic hardship related to the Great Depression ended all major commercial timber operations (Magnum 1997). By that time, clear cutting had left very few swaths of forest unharvested (Robinson 1994).

As timber harvesting and livestock grazing ceased in the 1940s, fire suppression became increasingly common in the Zuni Mountains and throughout the United States. Although the U.S. Forest Service began suppressing fires in the early 1900s, it was not until after World War II that fire suppression became effective enough to significantly disrupt wildfire in western forests (Covington and Moore 1994; Swetnam and Baisan 2003). Fire was perceived as the new enemy and war-like tactics such as smoke jumping became common practice (Grissino-Mayer and Swetnam 1997; Swetnam and Baisan 2003). Lookout towers, increased numbers of fire fighters, and advanced equipment such as aircraft changed the practice of fire suppression to a highly successful venture (Swetnam and Baisan 2003). The U.S. Forest Service's Smoky Bear campaign popularized the idea that wildfire should be eliminated from all natural environments, and images in Walt Disney's *Bambi* also fueled anti-wildfire sentiment (Dellasala *et al.* 2004). Consequentially, low-severity wildfire was virtually eradicated from many western forests (Arno and Allison-Bunnell 2002).

3.3.3.2 Beetle outbreak

According to a report by the U.S. Department of Agriculture (2009), bark beetles significantly affected approximately 43,000 acres (17,401 hectares) of ponderosa pine forests in the southwestern United States in 2008. In many western forests, insects are an important disturbance agent and interact with other disturbance agents including fire and wind (Baker and Veblen 1990; McHugh *et al.* 2003; Bigler *et al.* 2005; Kulakowski *et al.* 2007). In the Southwest, western pine beetle (*Dendroctonus brevicomis* LeConte) and various species of *Ips* beetles commonly attack ponderosa pine. These two taxa may occur in the same area and will even occupy the same individual tree host (USDA 2009). Although beetles usually kill only the oldest and weakest trees in a stand, they will attack young, healthy trees during epidemics (Schubert 1974).

3.4 Site characteristics

We established four sites in the Zuni Mountains in northwestern New Mexico (Figure 3.2). The nearest town is Grants, New Mexico, and our sites are approximately 120 km west of Albuquerque. Sites vary in elevation, topography, climate, soil type, and vegetation composition and structure. The size of each site also differs because the proximity and abundance of fire-scarred samples was inconsistent among sites. The Paxton Springs Cinder Cone site and the two Oso Ridge sites are part of Cibola National Forest and are managed by the U.S. Forest Service. The Bureau of Land Management site is at the boundary of El Malpais National Monument and, as the name implies, is managed by the Bureau of Land Management.

3.4.1 Paxton Springs Cinder Cone

The Paxton Springs Cinder Cone site is accessed from Forest Road 49 in the southeastern portion of the Zuni Mountains. Like most cinder cones, Paxton Springs Cinder Cone is steeply sloped and is composed of ash and scoria that erupted explosively as solids from the volcanic vent. Slower and less violent eruptions created the surrounding Zuni-Canyon lava flow (Laughlin and Perry 1997). The *Pinus ponderosa/*cinder soils habitat type (PIPO/Cinder HT) described by Alexander *et al.* (1987) best characterizes this site. Ponderosa pine is the dominant tree species and occurs in basaltic cinder soil. The soil is dry and unstable and thus promotes low stand density. The elevation range is greater at Paxton Springs Cinder Cone than at any of the other sites, and fire-history samples were collected from between 2,298 to 2,469 m. Frequent, historic wildfire along the base and flanks of the cinder cone is evidenced by the exceptional abundance and proximity of fire-scarred specimens. Logging did not occur at the top of the cinder cone

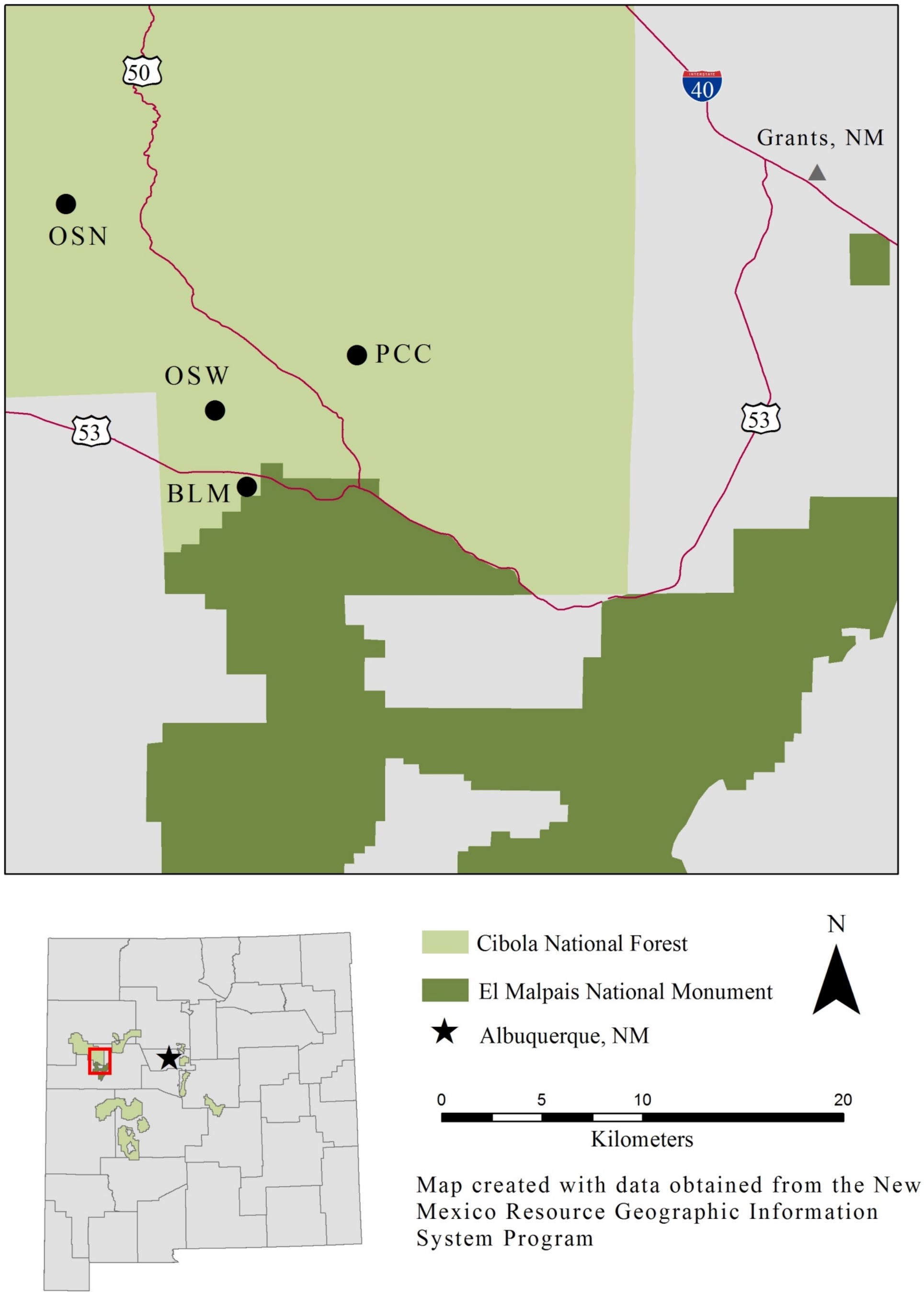

Figure 3.2 Study area map including all four sites in the Zuni Mountains, New Mexico.

(most likely because of its relative inaccessibility), and an old-growth stand still remains. Many of the trees at the top of the cone have lightning scars and/or show signs of severe beetle outbreak.

3.4.2 Oso Ridge sites

I established two sites along Oso Ridge in Cibola National Forest. Oso Ridge forms the backbone of the Zunis and consists of erosion-resistant sandstone that makes up a portion of the U.S. Continental Divide. The sites along the ridge range between 2,500 and 2,622 m in elevation and are the two highest elevation sites. Soils are relatively thick and well developed. The *Pinus ponderosa/Festuca arizonica* habitat type best describes the forest habitat type at both sites. Ponderosa pine is the dominant tree species with Arizona fescue abundant in the understory. A commonly occurring shrub species is *Quercus gambelii* Nutt. (Gambel oak) and its abundance varies greatly between sites. This habitat type is found at elevations ranging between 2,410 and 2,895 m and occurs along the lower to upper slopes of mountain ridges (Alexander *et al.* 1987).

3.4.2.1 Oso Ridge North

Oso Ridge North is the northernmost site and is located on the east side of Oso Ridge. A narrow and poorly maintained road that branches off Forest Road 50 provides access to the site. This area is relatively mesic and as a consequence the samples collected from stumps, snags, and logs were often heavily decayed. We collected samples between approximately 2,500 and 2,592 m. Fire-scarred samples often occurred in tight clusters, perhaps as a consequence of the heavily rolling topography at this site. The abundance of Gambel oak in the understory may indicate an absence of wildfire in recent years. The area has been heavily logged and is now a second-growth forest with many stumps and logs remaining. Unusual findings at this site included a vertically stacked double catface (fire-scar wound) on a stump, and at least one culturally-modified tree.

3.4.2.2 Oso Ridge West

The Oso Ridge West site is located along the southernmost portion of Oso Ridge. Forest Road 187 provides access to the site. Relief at the site is relatively minimal, with the exception of one steep south-facing slope. About half of the samples were collected from that slope, and the rest were spread out along a gently rolling topography. The elevation ranges between approximately 2,615 and 2,622 m. Historic logging was widespread and a nearby lookout tower may have facilitated fire suppression throughout the area. Private land that abuts this site provides an obvious contrast between land-management strategies, as forests are significantly denser and younger in the surrounding areas.

3.4.3 Bureau of Land Management

The Bureau of Land Management site is the southernmost site and is located along Highway 53 at the northern boundary of El Malpais National Monument. Although the Bureau of Land Management owns this site, the area is surrounded by National Park Service land to the south and U.S. Forest Service land to the north. The *Pinus ponderosa*/rockland habitat type best describes this site. Soils are very thin and exposed rock covers most of the ground surface (Alexander *et al.* 1987; Fitzhugh *et al.* 1987). Although historic logging occurred at the site, many of the older trees were left unharvested. Fire-scarred specimens are spread out across a large area and many samples are more than 1,000 m apart. Elevation ranges between 2,371 and 2421 m, and thus total relief is less than at other sites. Multiple catfaces are common, and one specimen (BLM 030) contained five individual catfaces.

CHAPTER FOUR

4. METHODS

4.1 Field methods

4.1.1 Fire history

The field crew for the fire-history work included Dr. Henri Grissino-Mayer, Ryan Foster, Ann McGhee, Niki Garland, Sarah Jones, Hunter Terrell, Kevin Russell, Nancy Li, the Lava Monsters fire crew of El Malpais National Monument, and myself. We identified and collected fire-history samples using well-established field methods (Arno and Sneck 1977; McBride 1983; Dieterich and Swetnam 1984; Baisan and Swetnam 1990; Caprio and Swetnam 1995). At each site, we first flagged all visibly fire-scarred trees, snags (standing dead trees), logs, remnants (portions of eroded logs), and stumps. We differentiated fire scars from other wounds and flagged only those trees that displayed typical signs of fire injury (Figure 4.1). Most often, this included evidence of repeated scarring on the basal portion of the tree bole in the form of a charred, inverted V-shaped wound (a “catface”). In steeply sloped areas, fires usually injure trees on the upslope side of the bole and thus we considered scar positioning around the base of the tree (Arno and Sneck 1977; McBride 1983; Grissino-Mayer and Swetnam 1997). We also examined the exposed cross-sectional surface of stumps for scar tips visible in annual rings. For all flagged samples, we recorded the location relative to known landmarks and then used a Garmin GPS receiver to determine the geographic coordinates.

After we flagged 50 or more samples per site, we chose approximately 30 to 35 of the best specimens for collection. This targeted sampling approach has been statistically

Figure 4.1 A fire-scarred stump at Oso Ridge West. The sample has repeated scarring on the basal portion of the tree bole and char along the scar ridges. Photo courtesy of William R. Foster.

validated and ensures that the fire record is both long and complete (Fulé *et al.* 2003; Van Horne and Fulé 2006). We mostly sampled dead material (stumps, logs, remnants, and snags), and gave preference to less-decayed specimens with solid wood around the scars. Before sampling, we photographed and sketched each sample and then recorded information such as the species, height, crown condition, and signs of injury. We used a Stihl 440 Magnum chain saw to extract complete cross sections from the bole through the fire-scarred surface (Figure 4.2). We also sampled partial cross sections from a maximum of four living trees per site. Partial cross sections are typically non-lethal and allow the researcher to obtain 20th and 21st century fire-history information (Arno and Sneck 1977; Baisan and Swetnam 1990; Van Horne and Fulé 2006; Heyerdahl and McKay 2008). After we removed each section, we immediately used permanent marker to label it with the sample ID number. In some cases, cross sections broke into multiple pieces and were illustrated and carefully labeled for later reassembly. We then wrapped our samples in several layers of industrial strength plastic wrap for transport back to the laboratory.

4.1.2 Chronology building

We relied on the principles of site selection and sensitivity (Fritts 1976) to choose one site for chronology building. We chose a stand of approximately 60 living ponderosa pine trees at the top of Paxton Springs Cinder Cone. We first flagged all living trees with a diameter at breast height $\geq$ 20 cm and then chose the oldest trees to core. Characteristics used to determine old age included low ratio of height to diameter, erratic growth forms, and heavy lower branches (Schulman 1954). We avoided trees with visible evidence of injury from lightning, fire, or insect

Figure 4.2 Use of a chain saw to extract a full cross section. Henri Grissino-Mayer collects a sample from Oso Ridge North. This sample was unusual because it contained a stacked double catface. Photo courtesy of William R. Foster.

outbreak to ensure that our chronology best captured the relationship between climate and tree growth (Fritts 1976). We used Haglöf increment borers to extract two cores from opposite sides of each tree at approximately 30 cm above the base. For trees positioned on a slope, we removed cores along the contour to avoid reaction wood (Fritts 1976; Grissino-Mayer 2003). We aimed to core through or near the pith of the tree, and when this did not occur, we extracted one or two additional cores. In some cases, rot prevented us from obtaining a complete core and we immediately removed the increment borer to prevent jamming inside the auger (Grissino-Mayer 2003). We inserted cores in paper straws labeled with the sample ID, diameter at breast height, species, date, and collector's initials, and then placed the samples into plastic map tubes for transport back to the laboratory.

4.2 Laboratory methods

4.2.1 Sample preparation

I first treated all cores and cross sections with insecticide to kill any insects still living in the wood. I then used wood glue to mount fragile cross sections on particleboard for stability. If cross sections were in multiple pieces, I relied on labels, illustrations, and photographs from the field to properly reassemble the parts. Increment cores were glued into customized wooden core mounts with the tracheids vertically aligned. Cores that were extremely twisted were carefully broken into a few pieces to ensure proper alignment in the mount. I allowed all cross sections and cores to dry completely and then sanded each sample using progressively finer grades of sandpaper (Stokes and Smiley 1968). I used a belt sander and began with ISO P-40 grit (425–500 µm) and finished with ANSI 400-grit (20.6–23.6 µm). Proper sanding procedures maximize the visibility of the wood's cellular structure and facilitate the crossdating process (Stokes and Smiley 1968; Orvis and Grissino-Mayer 2002).

4.2.2 Crossdating annual rings and standardization

I assigned exact calendar dates to the rings in each cross section using the technique of crossdating (Stokes and Smiley 1968; Fritts 1976). I first used statistical crossdating methods to obtain a general idea of where each cross section fit in time. I drew a transect of 100 undated years and then measured the widths of the annual rings to the nearest 0.001 mm using a stereoscopic boom-arm microscope with Measure J2X computer software. Ring-width measurements were then inputted in COFECHA computer software (Holmes 1983; Grissino-Mayer 2001a) as an undated series against a nearby reference chronology (Grissino-Mayer 1995). COFECHA is widely used to aid in the crossdating process and relies on segmented times series analysis. The program calculates numerous correlation coefficients to determine if ring-width patterns match across samples. Correlation coefficients that fall below a pre-designated critical threshold value ($r = 0.37$, $P < 0.01$) are flagged as problematic and must be re-examined (Grissino-Mayer 2001a). In the case of an undated series, COFECHA suggests a shift that will place the series in its appropriate place in time. I used the list method along with the COFECHA output to assign exact calendar years to each ring. In some cases, visual and statistical crossdating methods initially failed and it was necessary to draw a separate transect through a different section of the wood and repeat the process. Only when both visual and statistical methods confirmed crossdating did I assign firm calendar years to annual rings.

Exact calendar years were also assigned to the rings in 80 of the increment cores that were collected. Lab assistants Sarah Jones and Niki Garland assisted with this process. We generally dated two cores from each tree and began by dating relatively short series with clear annual rings. We then chose several of the oldest series to ensure adequate sample depth back to the year 1700. The procedure for crossdating cores was simpler than for cross sections because cores generally included bark. This made it possible to assign a calendar year to each ring by counting backwards from 2009 (the outermost partial ring) while using the list method to identify any missing or false rings (Stokes and Smiley 1968; Yamaguchi 1991). We then measured each core and used COFECHA to statistically verify crossdating. Lastly, we used ARSTAN (Cook 1985) to standardize the raw ring-width measurements for combination into a master chronology. Standardization transforms raw measurements into dimensionless indices, eliminates age-growth and disturbance trends, and averages raw data from multiple samples into a single index chronology (Fritts 1976). We detrended conservatively, using a negative exponential curve whenever possible to retain low-frequency climate information. When a negative exponential curve could not be fit to the data, ARSTAN defaulted to a negative linear regression line. In a few cases, the line still fell below the x-axis and a 100-year cubic smoothing spline was applied instead. Splines are slightly more flexible and were therefore better able to fit some of the data (Cook and Peters 1981).

4.2.3 Identifying and dating injuries

After crossdating each ring in the fire-scarred cross sections, I dated all visible injuries. I carefully examined each injury under a stereoscopic boom-arm microscope and relied on several characteristics to distinguish fire scars from scars caused by other factors such as mechanical injury. An injury was classified as a fire scar if it contained charcoal and followed a clear path through an individual ring. The presence of curved growth in subsequent rings and of vertical ridges along the charred surface served as further evidence of fire injury (Dieterich and Swetnam 1984) (Figure 4.3). After injury classification, I relied on the location of the scar tip in a crossdated annual ring to assign a calendar year to each scar. In most cases, I was also able to identify the season of scarring by examining the positioning of the scar tip in the earlywood or latewood (Dieterich and Swetnam 1984; Baisan and Swetnam 1990; Grissino-Mayer 1995; Grissino-Mayer *et al.* 2004) (Table 4.1).

4.3 Data analysis of fire history

4.3.1 Recorder years

I analyzed each cross section to determine recorder and non-recorder years. Recorder years are those years when a fire event would most likely be identifiable as a fire scar in an annual ring. A tree becomes a recorder after it is first scarred and sometimes continues to record until its death or sample date. In other cases, a tree may scar and then later revert back to non-recording. In this study, rings were classified as non-recorders when:

- The rings were positioned earlier in time than the first fire scar.
- Rings were too heavily decayed or distorted to identify scars.
- Subsequent fires burned off the outer portion of the rings where fires scars would have been located.

Figure 4.3 A crossdated sample from Paxton Springs Cinder Cone with fire scars labeled. The presence of char along the scar path and curved growth in subsequent rings are classic signs of injury from wildfire.

Table 4.1 Characteristics used to determine the seasonality of each fire scar.

Season	**Identifying Characteristics**
Dormant season fire (D)	Scar tip occurs between the latewood of the previous ring and the earlywood of the subsequent ring.[1]
Early season fire (E)	Scar tip occurs in the first one-third portion of the earlywood.
Middle season fire (M)	Scar tip occurs in the middle one-third portion of the earlywood.
Late season fire (L)	Scar tip occurs in the last one-third portion of the earlywood.
End of growing season fire (A)	Scar tip occurs in the latewood.
Unknown fire event (U)	Fire scar is present, but distortion or decay prevents seasonal assignment.

[1]Dormant scars may have formed either in early spring or late summer/fall. Because the exact seasonality of these scars cannot be determined, we followed convention and assumed that these scars formed as the result of a spring fire (Grissino-Mayer *et al.* 2004).

- The rings were located after (later in time) than a wound that had completely healed over.

Non-recording years are also known as “null” years and are excluded from statistical analyses. The researcher must take extreme care to properly distinguish recorder years from non-recorder years. The method of excluding null years from analysis produces more accurate (and typically shorter) fire-free intervals (Grissino-Mayer 2001b).

4.3.2 Software

I used Microsoft Excel to enter the fire-history data. For each sample, I entered the innermost date or pith date, the outermost date or bark date, and the years and seasons of fire scars and other injuries. I also identified all rings in the sample as recorder or non-recorder years. Next, I used FHX2 (Grissino-Mayer 2001b) to statistically analyze fire history. FHX2 is recognized as the standard for analysis of fire history in forest ecosystems where evidence from fire scars and other fire injuries in annual rings can be used to characterize historic wildfire regimes. The software includes tests that evaluate both spatial and temporal aspects of historic wildfire activity. I used FHAES Alpha 1.0 software (Sutherland *et al.* 2008) to graphically display fire-history information. FHAES was developed as an update to FHX2 software. Although FHAES strongly resembles FHX2 in function, I chose to use FHAES because its graphics module is compatible with Macintosh computers and because it graphically displays both sample depth and percent scarred as a part of each fire-history chart.

4.3.3 Fire-history and composite-filter charts

I created fire-history charts that depicted the master fire chronologies for each of my four sites. These charts allow for visual examination of past wildfire occurrence (Grissino-Mayer 2001b; Fulé *et al.* 2003). Patterns in fire frequency and synchrony are easily discernable. For each sample, horizontal lines run across the chart, beginning with the innermost ring or pith date and ending at the outermost ring or bark date. Solid, horizontal lines indicate that the years are recorders, while dashed lines indicate non-recorder years. Vertical, solid tick marks along the horizontal lines represent fire events. Samples are vertically stacked to allow the researcher to compare fire occurrence across samples.

I also created composite-filter charts for each site to complement my fire-history charts. These charts show the fire events that fall into three different percent-scarred classes: all fires, 10% scarred, and 25% scarred. Each filter required that fire events be recorded by two or more trees. The all-fires class is the most inclusive and contains both patchy and widespread fire events. In contrast, the 10% and 25% classes show a subset of fire years that are typically more widespread (Swetnam and Baisan 1996; Grissino-Mayer 2001b; Fulé *et al.* 2003). To compare the fire histories of all four sites simultaneously, I also created a combined composite-filter chart for each of the three percent-scarred classes. I then inspected all fire-history and composite-filter charts for spatial and/or temporal changes in wildfire occurrence. I specifically looked for differences in wildfire frequency and/or degree of synchrony within individual sites, and also among the four sites.

4.3.4 Fire-free interval analysis

4.3.4.1 Measures of central tendency

I used measures of central tendency calculated in FHX2 to analyze fire frequency at each of the four sites. I calculated the Weibull Median Interval and Weibull Modal Interval, which are both determined by modeling the fire-free interval data with the Weibull distribution. The Weibull distribution is more flexible than the normal distribution and provides a more reasonable fit for distributions of skewed data. The Weibull Median Interval is the fire-free interval that corresponds with the 50^{th} percentile of the fitted distribution and is relatively unresponsive to outliers. The Weibull Modal Interval, in contrast, represents the greatest amount of area under the probability density function. I also calculated the Mean Fire Interval for each site, which represents the average of all fire-free intervals. This measure is considered to be a less realistic estimate of fire frequency than the Weibull Median Interval and Weibull Modal Interval, but may be useful for comparison purposes (Grissino-Mayer 1999; Grissino-Mayer 2001b).

4.3.4.2 Measures of dispersion

I calculated the standard deviation and the coefficient of variation to assess the dispersion of my fire-free interval data. The standard deviation is a widely used measure of dispersion in statistics and is calculated by taking the square root of the variance. Approximately 68% of the data are contained within ±1 standard deviation, and 95% are within ±2 standard deviations. The coefficient of variation is another common measure of dispersion and is calculated by dividing the mean of the data by its standard deviation. Unlike the standard deviation, the coefficient of variation is a normalized measure of dispersion that allows for comparisons between fire-free interval distributions with unequal means or variances (Burt *et al.* 2009).

4.3.4.3 Measures of range

I calculated five statistics that describe the range of my fire-free interval data (Grissino-Mayer 1999; Grissino-Mayer 2001b):

- The Minimum Fire-Free Interval: The shortest actual fire-free interval.
- The Maximum Fire-Free Interval: The longest actual fire-free interval.
- The Lower Exceedance Interval: The 12.5th percentile of the Weibull distribution, delineating significantly short fire-free intervals.
- The Upper Exceedance Interval: The 87.5th percentile of the Weibull distribution, delineating significantly long fire-free intervals (Grissino-Mayer 2001b).
- The Maximum Hazard Interval: Derived from the Weibull hazard function to represent the maximum theoretical fire-free interval that an ecosystem can experience before a fire event becomes highly probable.

4.3.4.4 Temporal analyses of fire frequency

I began by examining my fire-history charts to determine what changes in fire activity may have occurred over time. I then conducted three statistical tests to determine if observed differences in fire frequency between periods were statistically significant at the 0.05 level. I ran two sets of tests. First, I compared the period 1700–1799 to the period 1800–1880. I conducted this comparison because fires during these periods may have been controlled by different climatic conditions (Grissino-Mayer and Swetnam 2000; Lewis 2003). Second, I compared the period 1700–1879 to the period 1880–2008, to test how changes in land use might have affected fire activity. For both sets of tests (1700–1799 and 1800–1880, 1700–1879 and 1880–2008), I conducted Student's *t*-tests, folded *F*-tests, and two-sample Kolmogorov-Smirnov (K-S) tests. Student's *t*-tests were used to assess differences in mean, folded *F*-tests were conducted to assess differences in variance, and two-sample K-S tests were used to assess differences in distributions (Grissino-Mayer 2001b).

4.3.4.5 Spatial analyses of fire frequency

My spatial analyses also applied Student's *t*-tests, folded *F*-tests, and two-sample K-S tests. I first compared fire chronologies of each site to determine what differences might exist among sites. Significant differences ($P < 0.05$) would indicate that fire frequency at individual sites were statistically unique. These differences could have resulted from a variety of factors, including variability in habitat type, elevation, soil type, vegetation structure, and/or land-use changes. I also compared the fire chronologies of my four sites to other chronologies from sites in El Malpais National Monument to determine what differences might exist between fire regimes of the Zuni Mountains and those of the National Monument. To accomplish this comparison, I combined my four sites using the merge function in FHX2 and then compared this combined file to a file created from four merged sites near the northern boundary of El Malpais

National Monument (Cerro Bandera East, Cerro Bandera North, Candelaria, and La Marchanita) (Grissino-Mayer 1995).

4.3.5 Fire seasonality analyses

I analyzed the seasonality of fire activity across my study area. I designated early-season fire events as those that corresponded with dormant (D) or early (E) fire scars. In contrast, late-season fire events corresponded with fire scars assigned as middle (M), late (L), or latewood (A) (Allen 1989; Grissino-Mayer and Swetnam 2000; Grissino-Mayer *et al.* 2004). To determine the fire season that was most common during the period of analysis (1700-1880), I compared the percentage of early- vs. late-season scars at each site. I then assessed changes in seasonality that might have occurred over time by comparing the proportion of early-season scars to the proportion of late-season scars during the period 1700–1799 to that of 1800–1880. Finally, I combined the data from all sites into one large set to assess changes in seasonality at a finer temporal scale and broader spatial scale. I examined the proportion of early- versus late-season scars in nine contiguous 20-year intervals for the period 1700 to 1880.

4.4 Fire-climate analyses

4.4.1 Superposed Epoch Analyses

I conducted Superposed Epoch Analyses in JEVENT software (Grissino-Mayer 2001b) to examine how various climate variables might influence wildfire activity (Grissino-Mayer and Swetnam 2000; Grissino-Mayer 2001b; Hessl *et al.* 2004; Schoennagel *et al.* 2005, 2007; Taylor and Beaty 2005). Fire years from the 25% scarred class for all sites combined were used to target the relationship between climate and widespread fire (Appendix 1). I used reconstructed climate data for precipitation, the Palmer Drought Severity Index (PDSI), ENSO, and PDO to test whether certain climatic conditions were common prior to, during, or following a fire event (Table 4.2). Reconstructed data were required because instrumental data are not available for the full period of the fire record. These data were downloaded from the National Climate Data Center. Several reconstructions were available for each climate variable and I gave preference to reconstructions that were widely used in the literature and were developed from tree-ring chronologies proximal to our study area. In JEVENT, I chose a window of ten years (beginning six years prior, and ending three years after a fire event). Bootstrapping methods were used to generate confidence intervals. When the mean value exceeded one or more confidence intervals, climate conditions were found to significantly influence fire activity (Grissino-Mayer 2001b).

4.4.2 Chi-Square analysis

I conducted a chi-square goodness-of-fit test to examine fire behavior during the various phase combinations of ENSO and PDO (Schoennagel *et al.* 2005, 2007; Heyerdahl *et al.* 2008). I focused specifically on widespread fires, which were defined as scarring 25% or more of the samples (Appendix 1). My goal was to determine whether the distribution of widespread fire years among the four phase combinations (+ENSO/+PDO, +ENSO/–PDO, –ENSO/–PDO, –ENSO/+PDO) differed significantly from the distribution of all years among phase combinations independent of fire activity. Significant results would suggest that PDO-ENSO patterns were influential to widespread fire occurrence during the period of analysis (1700–1880).

Table 4.2 Tree-ring based climate reconstructions used for statistical analyses.

Climate Variable	Source of Reconstruction	Additional Details
Precipitation	Grissino-Mayer 1995, 1996	A 2129 year long reconstruction of precipitation for northwestern New Mexico, USA. Based on a water year from previous July to current July.
Palmer Drought Severity Index	Cook *et al.* 2004	This reconstruction included unique values for a large gridded network derived from 388 tree-ring chronologies. For this study, data were downloaded for Gridpoint 119 in northwestern New Mexico, and extended back to A.D. 0.
El Niño-Southern Oscillation	Cook *et al*. 2008	This 700 year long reconstruction was based on tree-ring data from Texas and Mexico. Data for Niño 3.4 were used.
Pacific Decadal Oscillation	D'Arrigo *et al*. 2001	This 300 year long reconstruction was based on western North American tree-ring records.

4.5 Climate/tree-growth analyses

4.5.1 Software and data input

I used DENDROCLIM2002 (Biondi 1997; Biondi and Waikul 2004) to assess the relationship between climate and tree growth in our study area using both correlation and response function analyses. I first considered using PRECON, a software program that develops a bioclimatic model of tree growth and describes how much of the variance is explained by each climate variable in response function analysis. However, I chose DENDROCLIM2002 because of its ability to calculate bootstrapped confidence intervals that more accurately test for significance (Efron and Tibshirani 1986; Biondi and Waikul 2004).

Input data needed for DENDROLIM2002 were monthly climate data and tree-ring index values. I downloaded instrumental precipitation and temperature data from the National Climatic Data Center, and instrumental data for PDSI from the Climate Explorer website produced by the Royal Netherlands Meteorological Institute. In both cases, data were downloaded for Division One of New Mexico for the period 1930 to 2008. Although instrumental records were available for earlier years, I excluded these data because earlier records tend to be less accurate. The standard tree-ring chronology developed for Paxton Springs Cinder Cone was used. My window of analysis ranged from May of the previous growing season through November of the current growing season to account for the influence of both past and present growing conditions (Fritts 1976).

4.5.2 Correlation analyses

I used correlation analyses to test the association between various climate variables and tree growth. Correlation analysis measures the linear relationship between two variables and results in a value between +1 and −1. Positive values indicate that both variables increase simultaneously, while negative values indicate that as one variable increases, the other decreases. The relationship becomes stronger as the correlation approaches +1 or −1, and an associated *P*-value < 0.05 is typically required for significance (Burt *et al.* 2009). In DENDROCLIM 2002, data are assumed to be normal and so correlation analyses generate Pearson product-moment correlation coefficients between monthly climate variables and ring-with indices.

4.5.3 Response function analyses

I conducted response function analyses to complement the correlation analyses of the climate/tree-growth relationship. Response function analysis is a widely applied technique that uses principal components multiple regression to estimate indexed values of ring-width growth. The products of the regression coefficients and the principal components are then calculated to obtain a new set of regression coefficients related to the original climate data (Briffa and Cook 1990; Biondi and Waikul 2004). An advantage of response function analysis over correlation analysis is that response function analysis removes the effects of interdependence among the climate variables (Fritts 1976). When correlation and response function analysis are conducted together in DENDROCLIM2002, response function analysis typically identifies fewer significant relationships than correlation analysis.

CHAPTER FIVE

5. RESULTS

5.1 Crossdating and chronology construction

I crossdated 806 fire scars on 75 specimens of ponderosa pine from four sites in the Zuni Mountains. Although false and missing rings occasionally challenged the crossdating process, most samples dated easily against a reference chronology from El Malpais National Monument (Grissino-Mayer 1995). Especially narrow rings aided the visual and graphical crossdating and included: 1733, 1735, 1748, 1773, 1785–1786, 1806, 1822, 1847, 1880–1881, 1904, and 1951. I also relied on wide rings, such as a series of seven wide rings (1766 to 1772) that preceded a decade of narrow rings (1773 to 1782) on most samples. Widespread fires in 1773, 1805, 1810, 1826, and 1870 further aided crossdating. These fires scarred 25% or more of the samples at a minimum of three of the four sites. The majority of cross sections had innermost or pith dates between 1600 and present, but one sample (BLM 037) crossdated with a pith date of 1487.

I also crossdated 80 increment cores from a stand of old-growth ponderosa pine at the top of Paxton Springs Cinder Cone (Figure 5.1; Table 5.1; Appendix 2). The same wide and narrow marker rings that aided the crossdating of cross sections also facilitated the crossdating of cores. The master chronology included series from 43 trees (generally two per tree) and extended from 1649 to 2008 (360 years). Individual series ranged in length from 60 to 360 years. The average mean sensitivity was 0.43 and the interseries correlation was $r = 0.76$ ($P < 0.001$). I visually inspected the few flagged segments in the chronology ($n = 5$, 0.8%) to ensure proper dating and determined that a reduced climate signal explained low correlation values, rather than misdating. This reduced signal was likely due to erratic growth from disturbance.

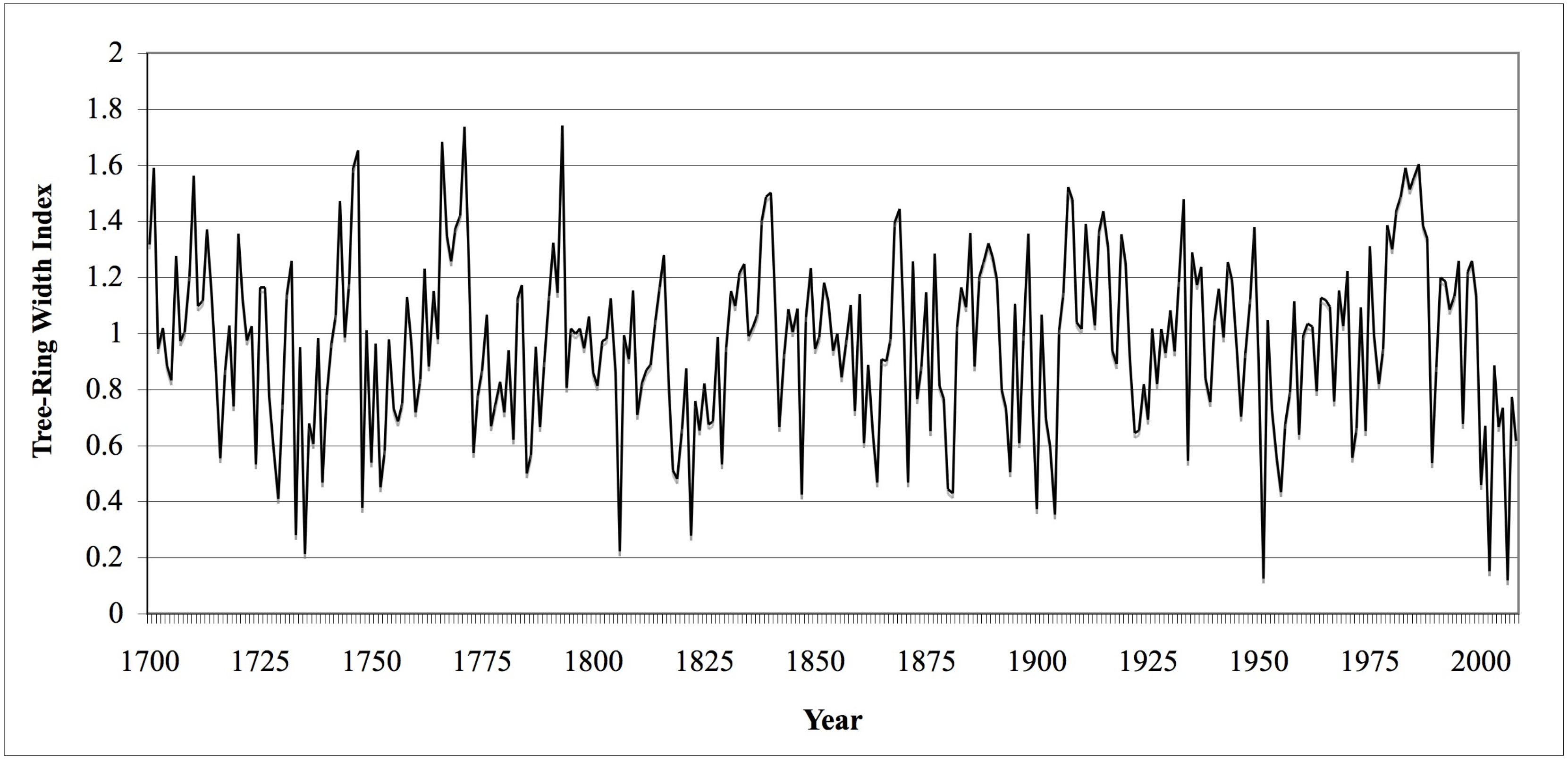

Figure 5.1 The standard tree-ring chronology for Paxton Springs Cinder Cone for the period 1700 to 2008.

Table 5.1 Summary information for the tree-ring chronology from Paxton Springs Cinder Cone.

Statistic	
Number of dated series	80
Number of dated trees	43
Interseries correlation	$r = 0.76$ ($P < 0.001$)
Average mean sensitivity	0.43
Number of flagged segments	5
Total number of segments tested	601
Mean length of individual series (yr)	184.6
Length of master series (yr)	360

5.2 Fire history

5.2.1 Master fire chronologies

5.2.1.1 Bureau of Land Management

The Bureau of Land Management chronology was the longest of the four master fire chronologies, and extended 523 years (Table 5.2; Figures 5.2, 5.3, and 5.4). Sample depth remained low until the early 1700s, with only some evidence of fire events during the 15th, 16th, and 17th centuries. The master chronology contained 19 samples that recorded 45 unique fire events. Samples included on average 10 fire scars, and one sample recorded over 20 fire events (BLM 23, n = 21). Although the master chronology indicated that fires occurred often between 1700 and 1880, fires became increasingly synchronous and widespread beginning around 1795. Numerous fires over the next several decades scarred at least 50% of the samples, including fires in 1795, 1800, and 1805. A widespread fire occurred in 1880, and then fire frequency decreased sharply. The last widespread fire event occurred in 1921 after an atypically long fire-free interval of 18 years.

5.2.1.2 Oso Ridge North

The Oso Ridge North master fire chronology extended from 1566 to 2009 (444 years). The chronology contained 18 samples that recorded 52 unique fire events, more than at any other site (Table 5.2; Figures 5.5, 5.6, and 5.7). I dated an average of 11 fire scars per sample, although a third of the samples (n = 6) contained 15 or more fire scars. The earliest fire scar dated to 1625, but fire events became more common in the 1700s and 1800s. Fire frequency at Oso Ridge

Table 5.2 Sample information for all master fire chronologies.

Site	Number of Samples	Number of Fire Scars	Chronology Length (yr)	Fire Scars per Tree		
				Min.	Max.	Mean
BLM	19	186	523	3	21	10
OSN	18	198	444	1	21	11
OSW	18	221	492	2	24	12
PCC	20	201	435	3	21	10
Total	75	806	--	--	--	--

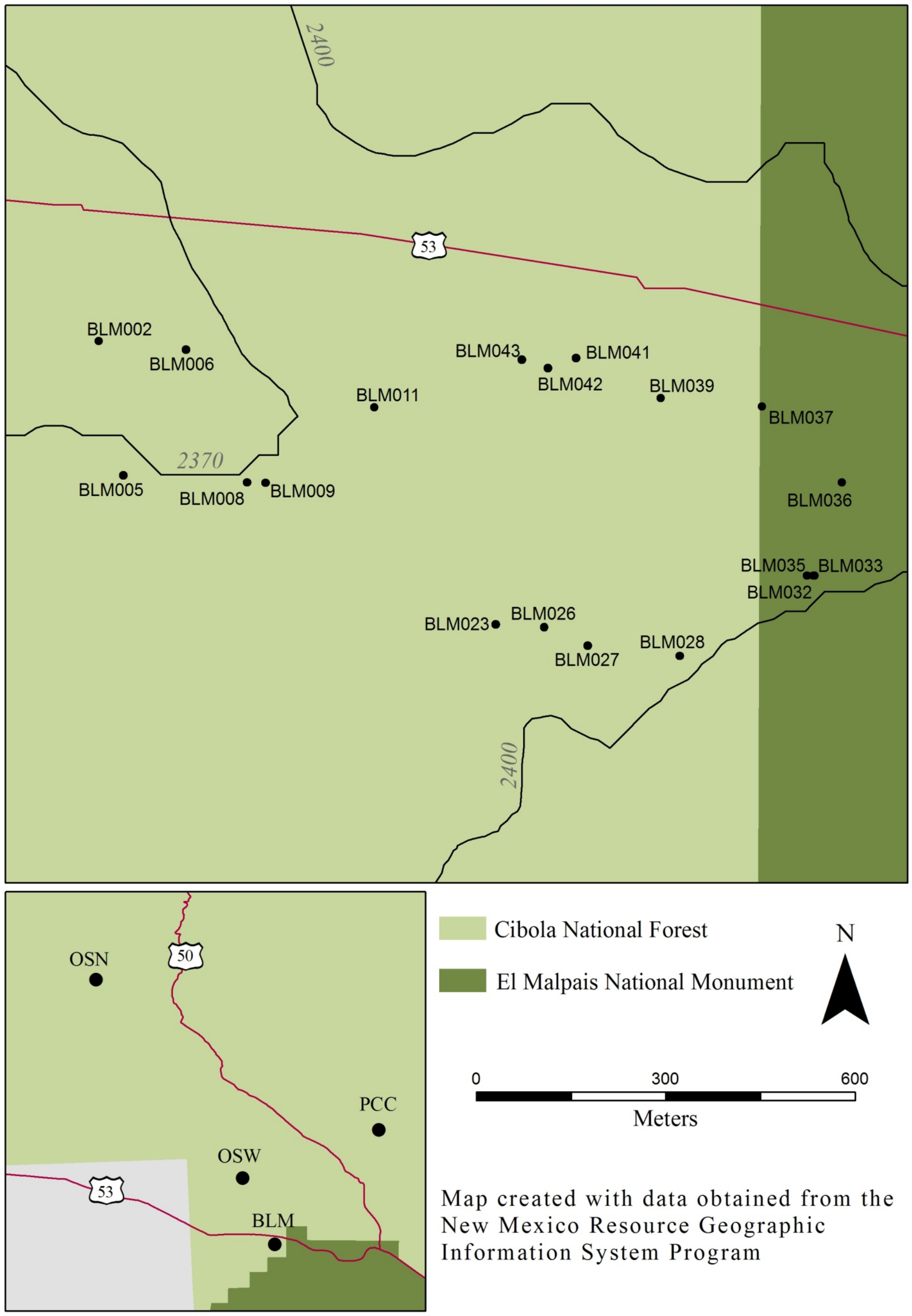

Figure 5.2 Location of fire-scarred samples at the Bureau of Land Management site.

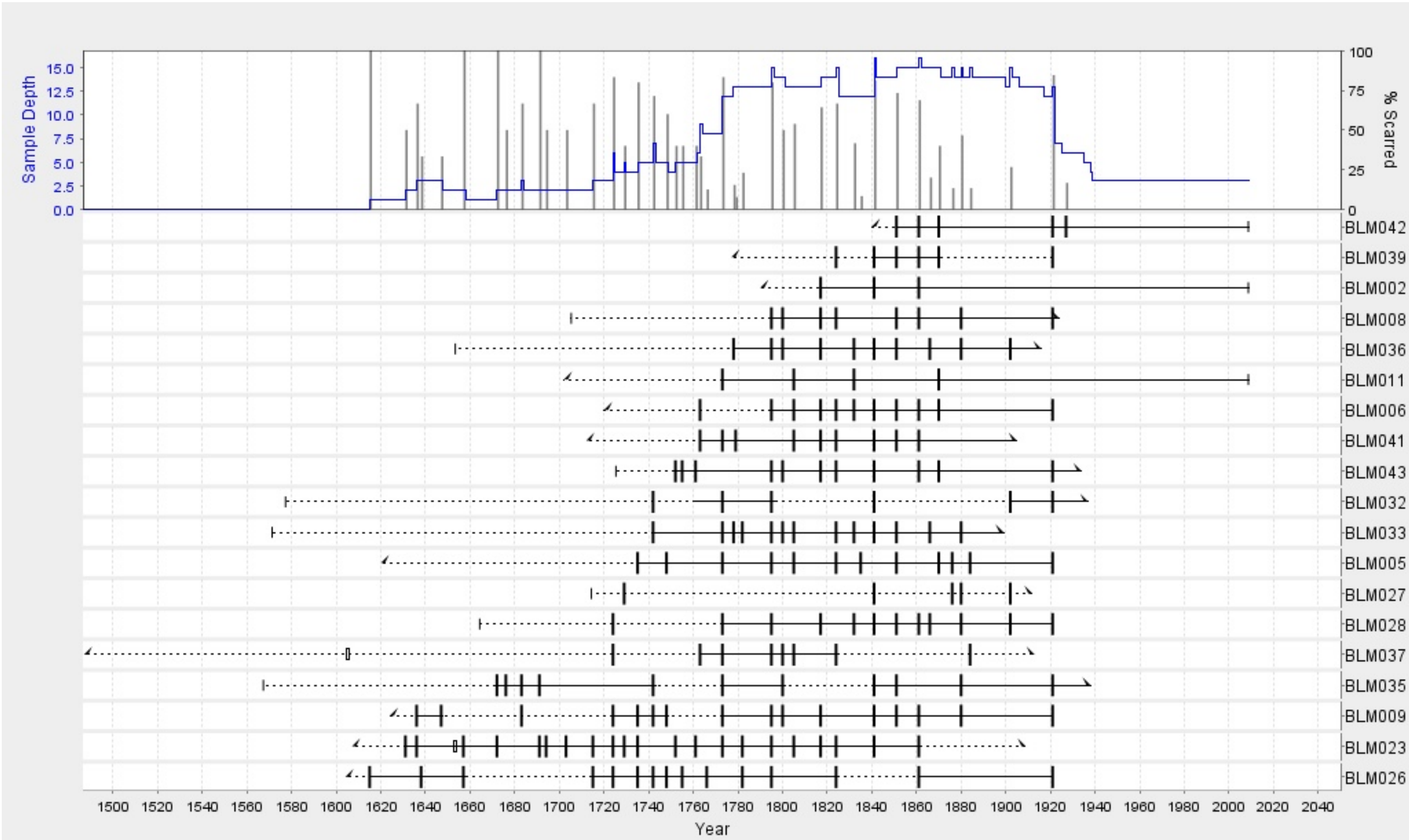

Figure 5.3 Master fire chronology of the Bureau of Land Management site. Dashed portions of each horizontal line indicate non-recorder years while solid lines indicate recorder years. Long, vertical tic-marks indicate a year when the sample recorded a fire. Shorter, hollow tick-marks indicate other injuries that may or may not be fire-related.

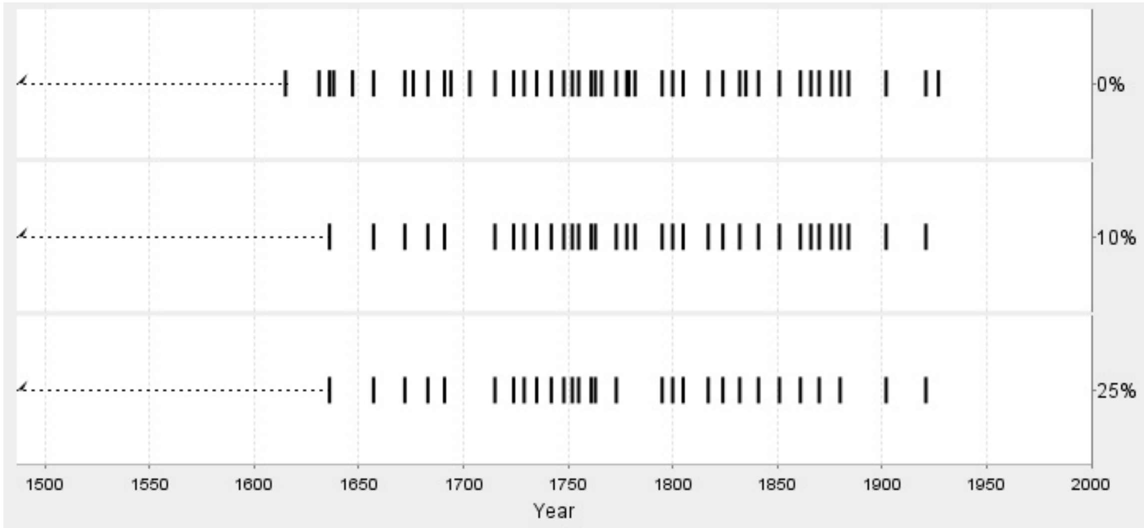

Figure 5.4 Composite filters for the Bureau of Land Management site. Vertical lines represent fire years included in each filter. The 0% filter included all fires, the 10% filter included fires that scarred at least 10% of the samples, and the 25% filter included fires that scarred at least 25% of the samples.

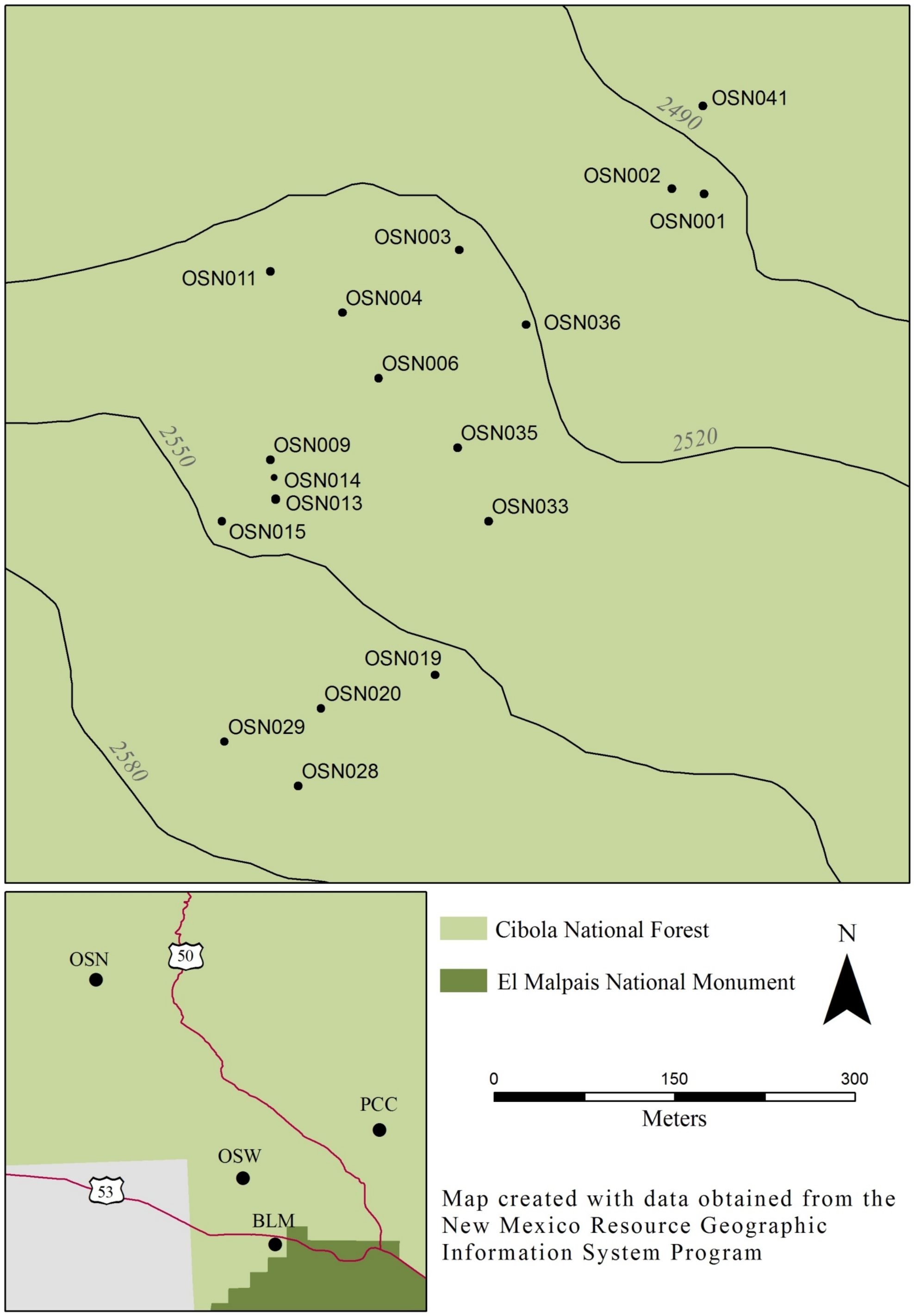

Figure 5.5 Location of fire-scarred samples at the Oso Ridge North site.

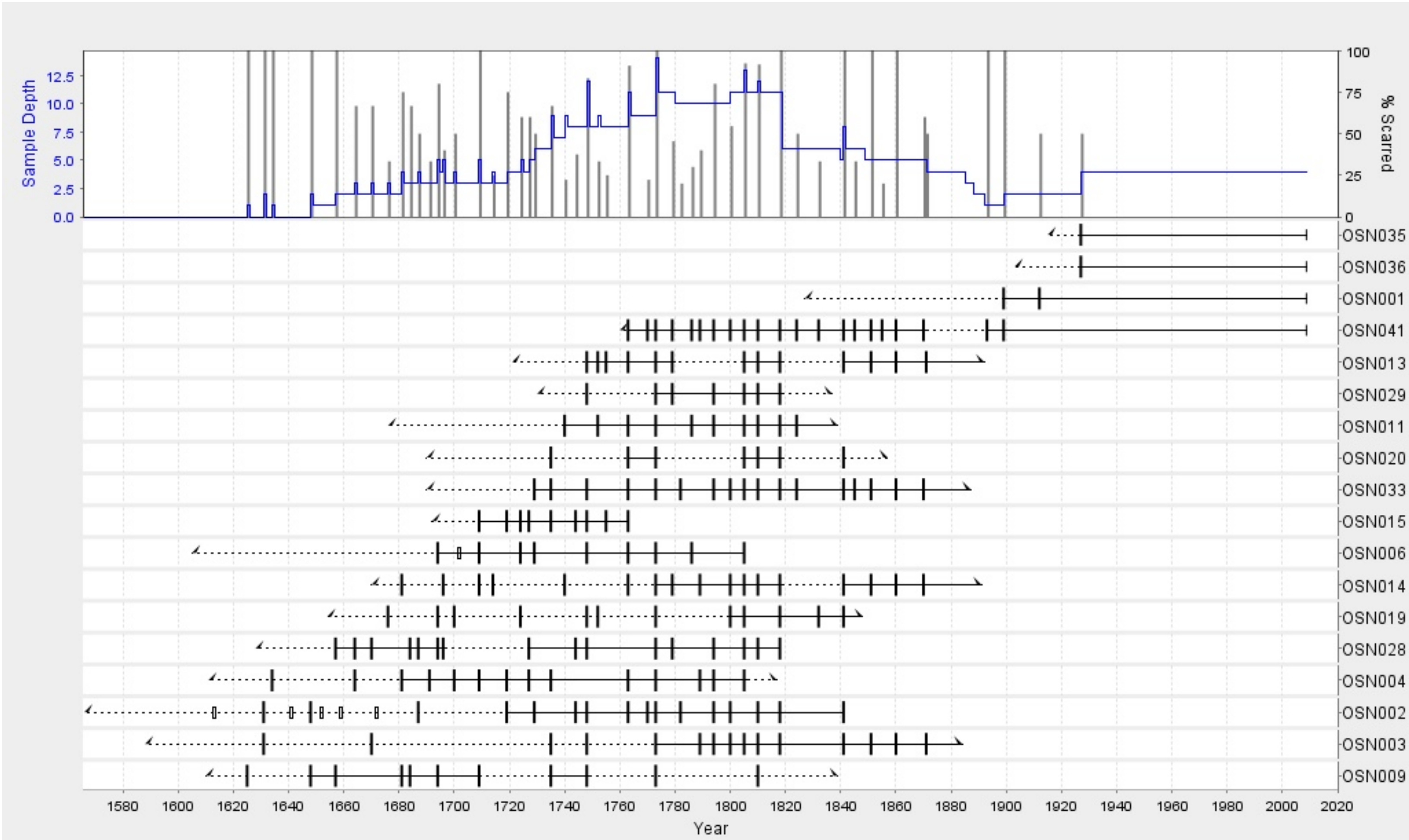

Figure 5.6 Master fire chronology of the Oso Ridge North site. Dashed portions of each horizontal line indicate non-recorder years while solid lines indicate recorder years. Long, vertical tic-marks indicate a year when the sample recorded a fire. Shorter, hollow tick-marks indicate other injuries that may or may not be fire-related.

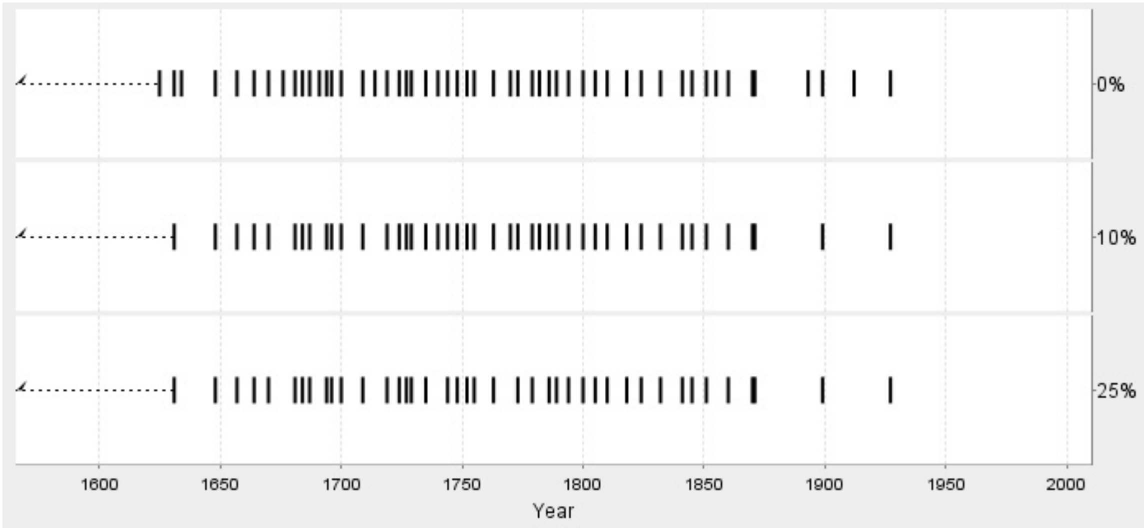

Figure 5.7 Composite filters for the Oso Ridge North site. Vertical lines represent fire years included in each filter. The 0% filter includes all fires, the 10% filter includes fires that scarred at least 10% of the samples, and the 25% filter includes fires that scarred at least 25% of the samples.

North decreased in the late 1800s, earlier than at other sites. A fire in 1860 scarred all of the samples (n = 6) and then two separate fires scarred about half of the samples in 1870 and 1871. The last fire event in the chronology occurred in 1927 and scarred only two samples.

5.2.1.3 Oso Ridge West

The Oso Ridge West master fire chronology extended from 1518 to 2009 (492 years) and included 18 samples that recorded 41 unique fire events (Table 5.2; Figure 5.8, 5.9, and 5.10). On average, each sample contained 12 scars. Sample OSW 018 recorded more fire events than any other sample from any site (n = 24). The first fire in the chronology occurred in 1638 and scarred both samples that were capable of recording fires. These samples were collected from stumps that were approximately 200 m apart. Fires occurred relatively frequently and synchronously from 1693 to 1878 and thus the late 1700s change to increasingly widespread, synchronous fires observed at other sites was not evident at Oso Ridge West. No fire events were identified to have occurred in the 20th century. The latest fire event took place in 1896 and scarred 10 of the 12 samples that were capable of recording fires.

5.2.1.4 Paxton Springs Cinder Cone

The master fire chronology from Paxton Springs Cinder Cone included 20 samples with evidence of 39 unique fire events (Table 5.2; Figure 5.11, 5.12, and 5.13). The chronology was the shortest of the four chronologies and extended from 1575 to 2009. With the exception of a fire event in 1684, all fires occurred after 1700. Each sample contained on average 10 scars, although two samples (PCC 005 and 008) recorded 21 and 20 fire events, respectively. The most

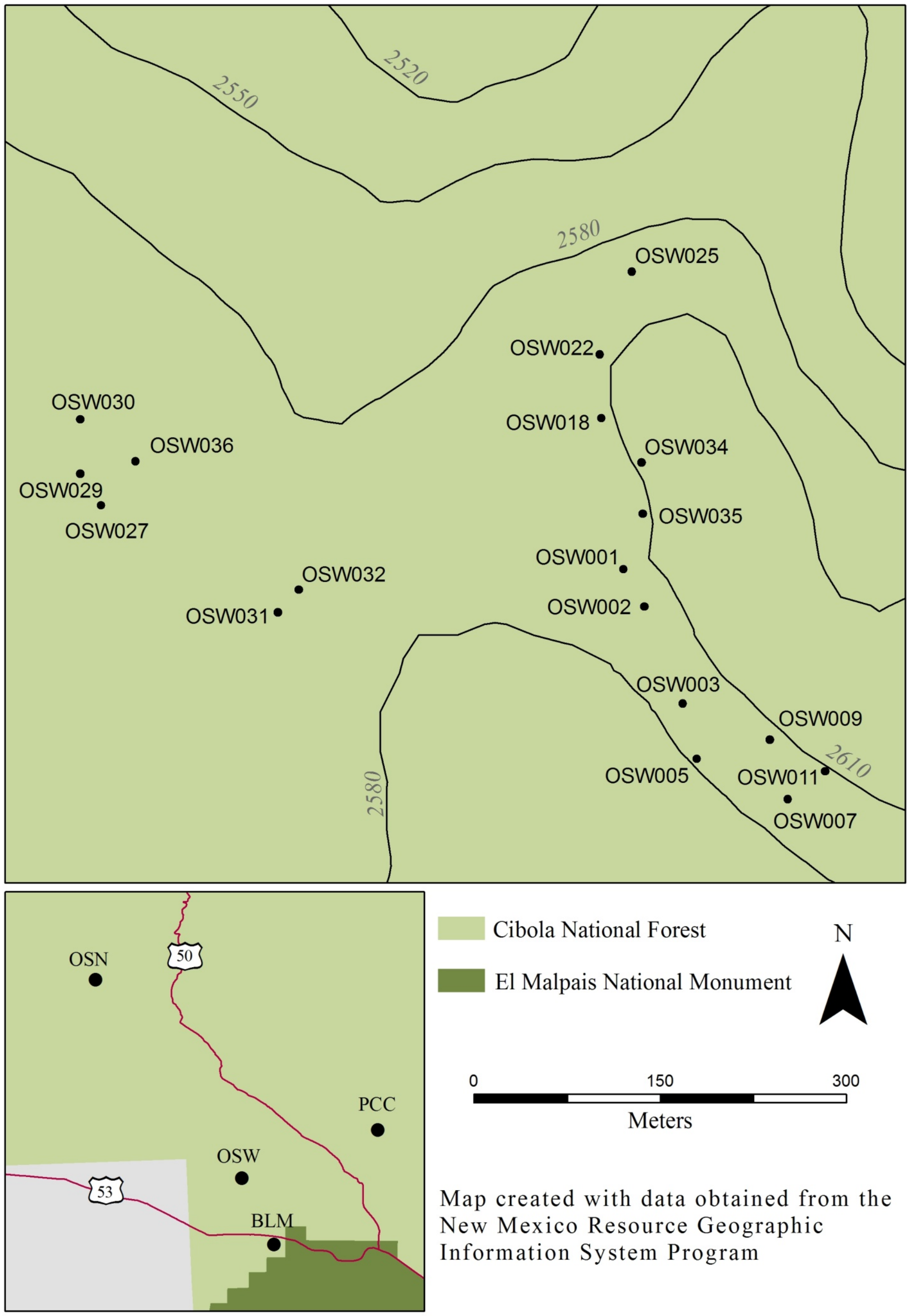

Figure 5.8 Location of fire-scarred samples at the Oso Ridge West site.

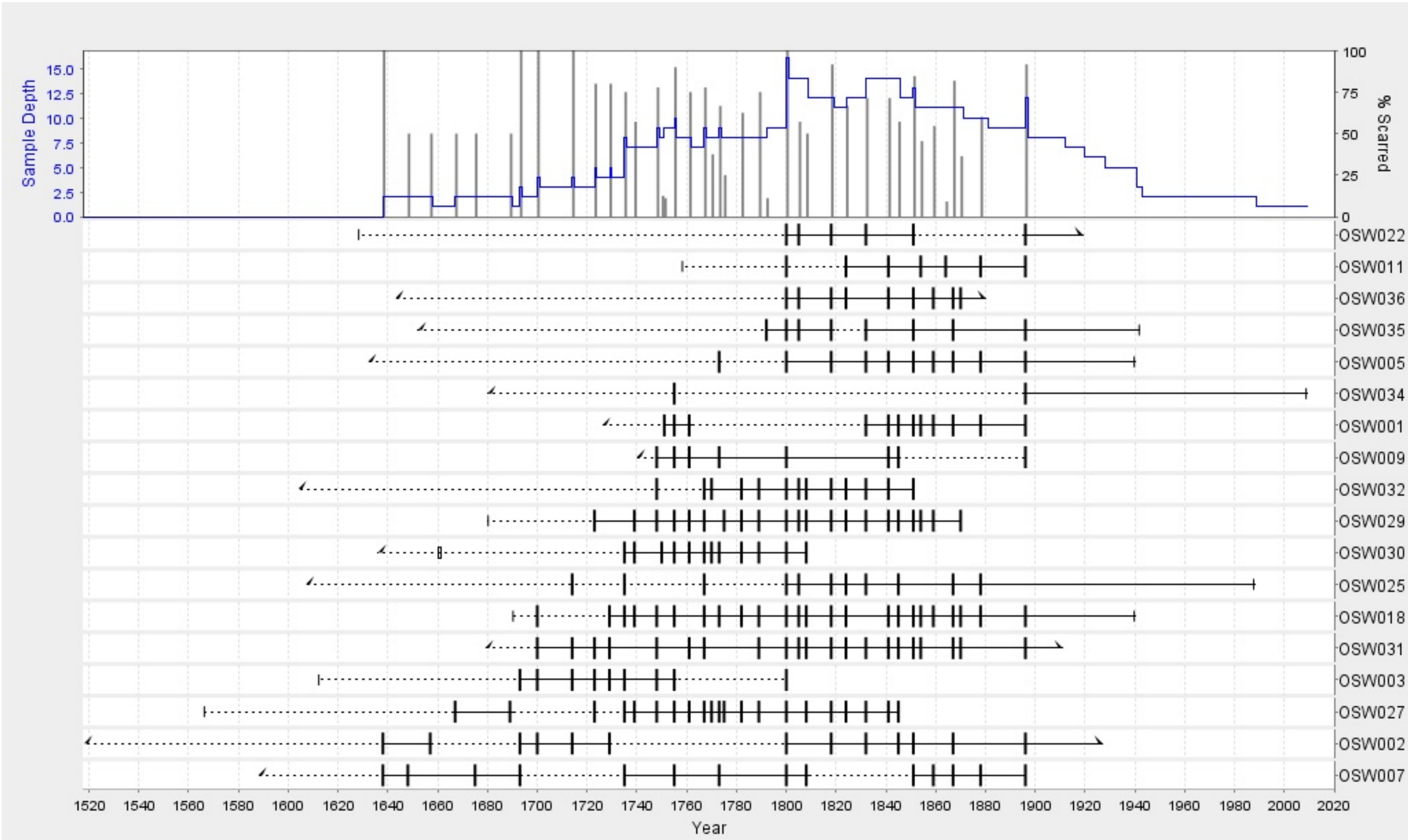

Figure 5.9 Master fire chronology of the Oso Ridge West site. Dashed portions of each horizontal line indicate non-recorder years while solid lines indicate recorder years. Long, vertical tic-marks indicate a year when the sample recorded a fire. Shorter, hollow tick-marks indicate other injuries that may or may not be fire-related.

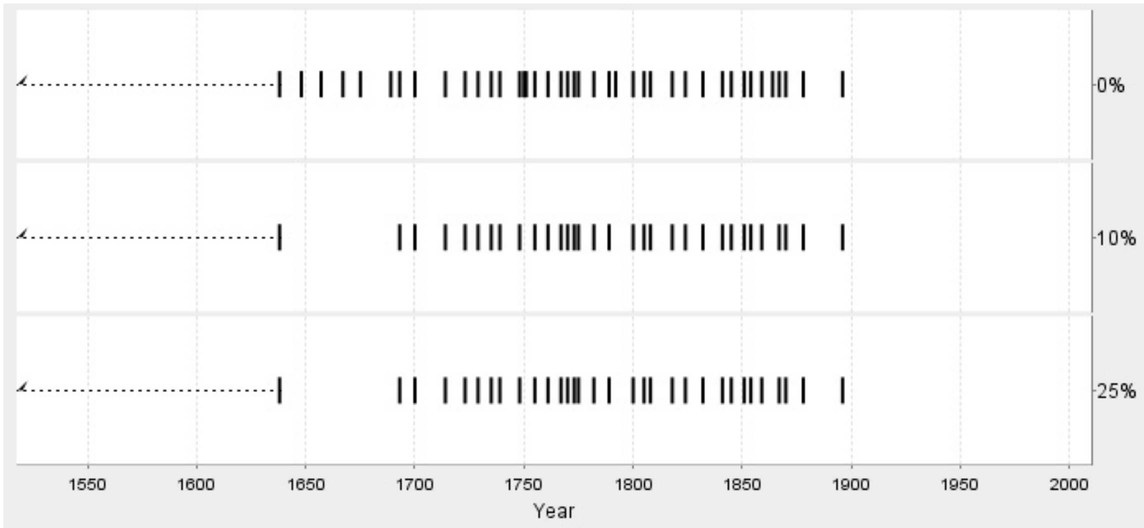

Figure 5.10 Composite filters for the Oso Ridge West site. Vertical lines represent fire years included in each filter. The 0% filter included all fires, the 10% filter included fires that scarred at least 10% of the samples, and the 25% filter included fires that scarred at least 25% of the samples.

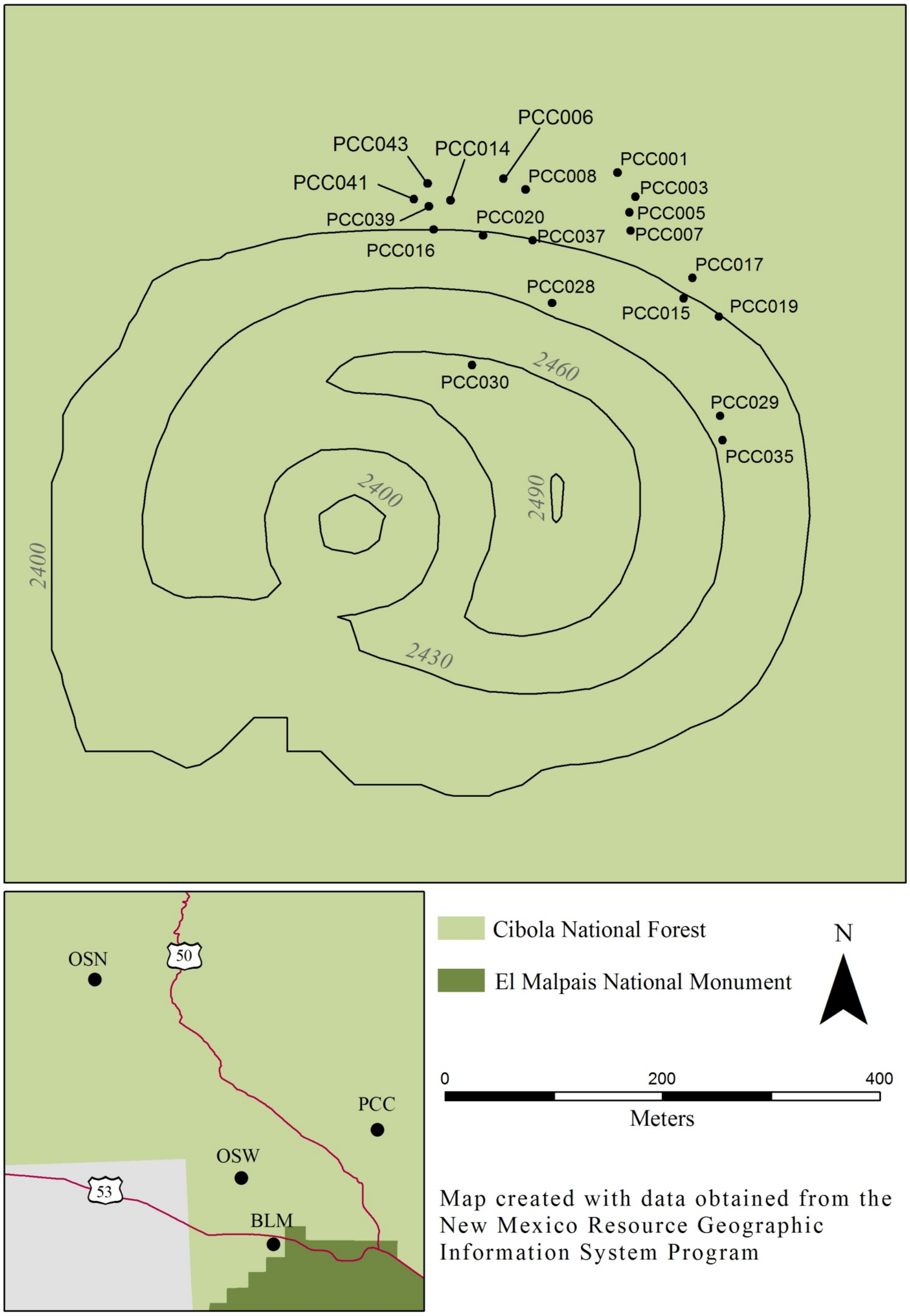

Figure 5.11 Location of fire-scarred samples at the Paxton Springs Cinder Cone site.

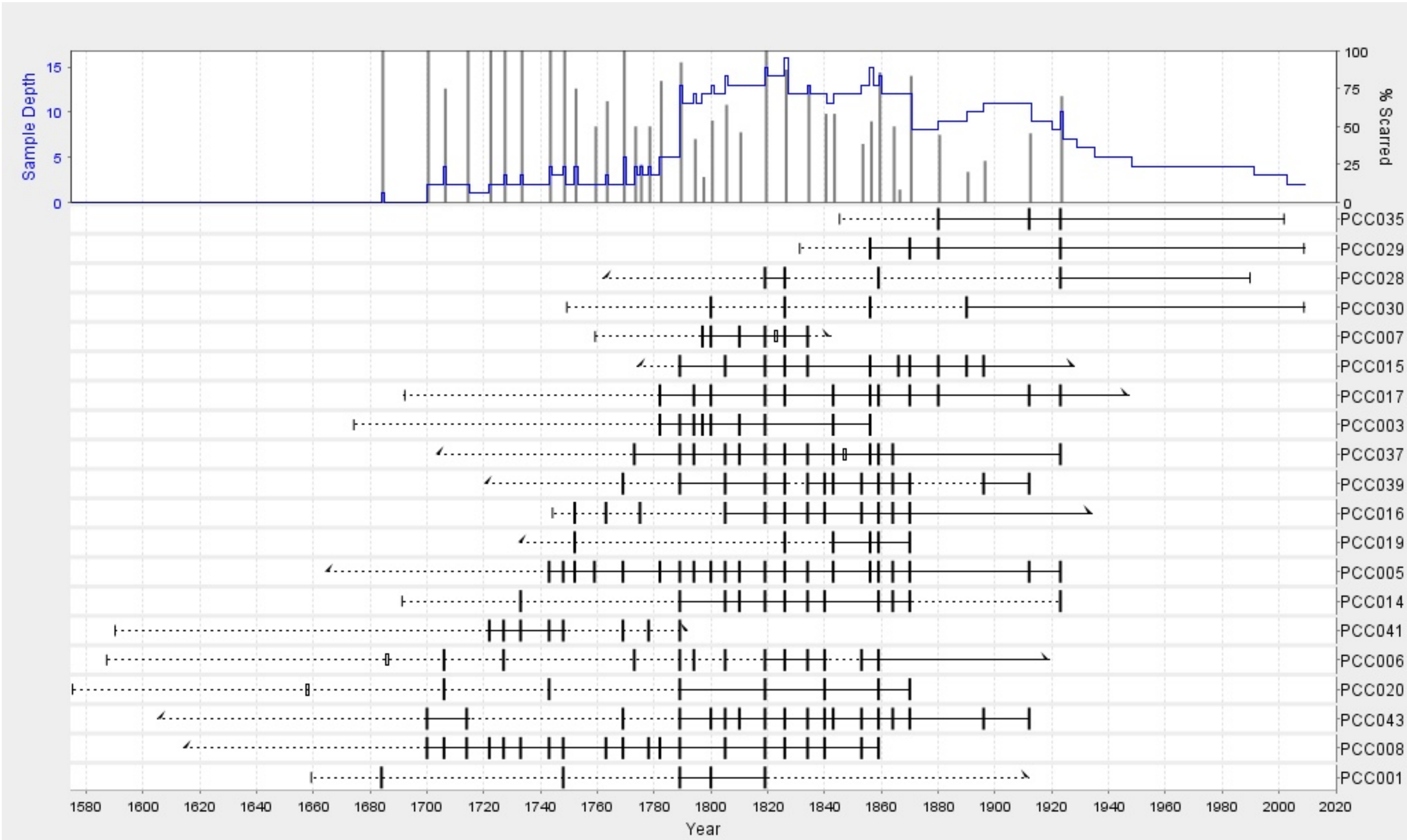

Figure 5.12 Master fire chronology of the Paxton Springs Cinder Cone site. Dashed portions of each horizontal line indicate non-recorder years while solid lines indicate recorder years. Long, vertical tic-marks indicate a year when the sample recorded a fire. Shorter, hollow tick-marks indicate other injuries that may or may not be fire-related.

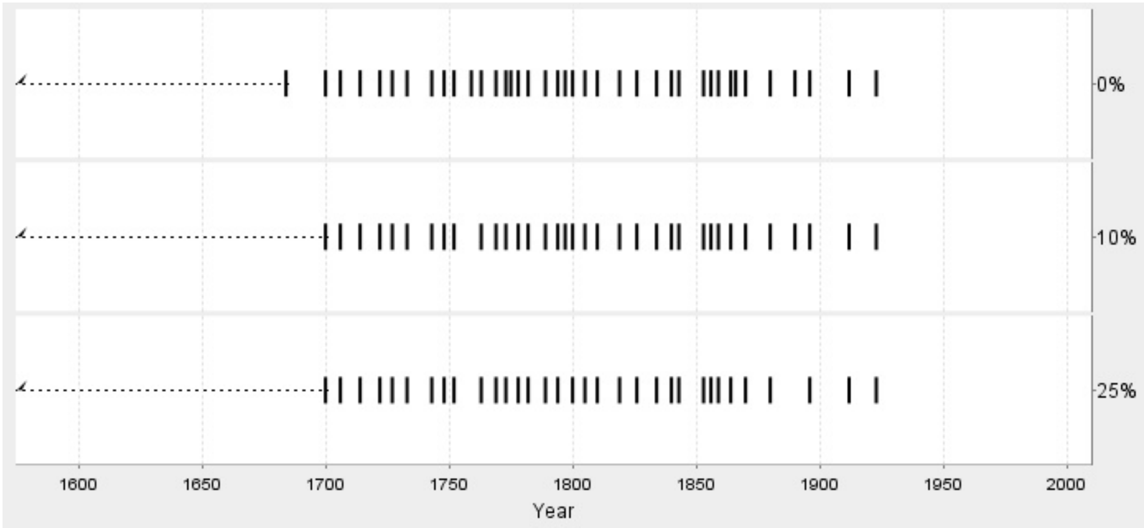

Figure 5.13 Composite filters for the Paxton Springs Cinder Cone site. Vertical lines represent fire years included in each filter. The 0% filter included all fires, the 10% filter included fires that scarred at least 10% of the samples, and the 25% filter included fires that scarred at least 25% of the samples.

widespread fire of the 1700s occurred in 1789 and scarred all but 1 of the 12 samples that were capable of recording fires. In the 1800s, fires occurred more frequently at Paxton Springs Cinder Cone than at other sites, and several widespread fires occurred only three years apart (1840 and 1843; 1853, 1856, and 1859). Fires become less frequent and synchronous after 1870, although fires scarred at least 20% of the samples in 1880, 1890, 1896, 1912, and 1923.

5.2.1.5 Comparison among sites

Comparison of the master fire chronologies from the four sites revealed similarities and differences among fire regimes (Figure 5.14). In terms of chronology length, the Bureau of Land Management and Oso Ridge West chronologies were longer than those from Paxton Springs Cinder Cone and Oso Ridge North, but all chronologies exceeded 400 years in length. Sample depth also varied among sites, with the Bureau of Land Management chronology containing many more samples dating back to the 17th century than the other chronologies. The average number of fire scars per sample was similar among sites (10 to 12 scars). Each site experienced one or more patchy fires that did not occur anywhere else in the study area. However, widespread fires that occurred at multiple sites were also common, and a large proportion of all fires (25%) occurred in three or more of the studied sites. Fire frequency decreased suddenly at all sites in the late 19th century, but the timing and steepness of the decline varied by site. Fires in the 20th century were rare, but did occur at all sites except Oso Ridge West. The last fire event recorded at any site took place in 1927 and scarred trees at the Oso Ridge North and Bureau of Land Management sites.

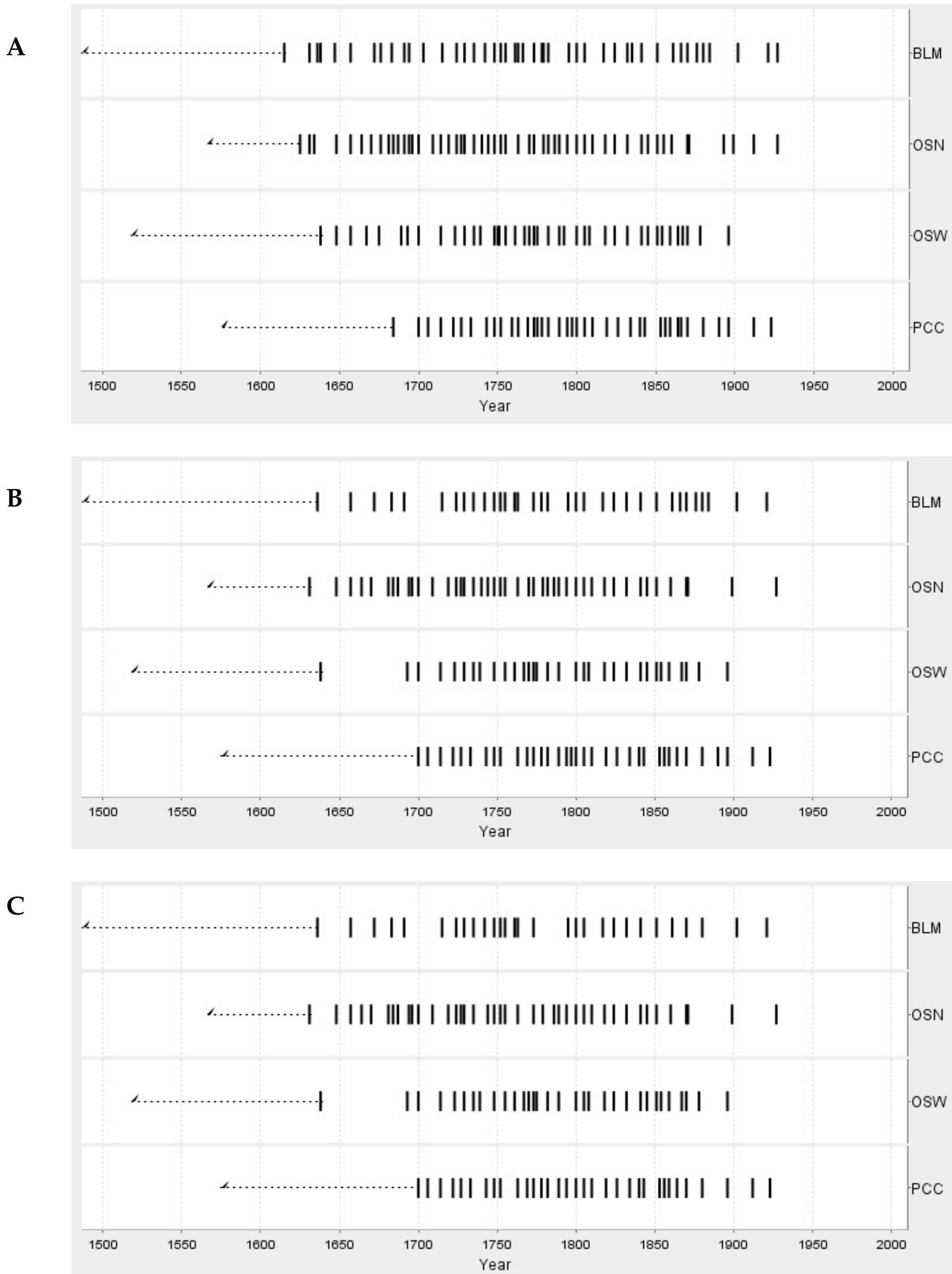

Figure 5.14 Composite filters for each site for (A) all fires (B) fires that scarred at least 10% of the samples, and (C) fires that scarred at least 25% of the samples. Vertical tic-marks represent fire years included in each filter

5.2.2 Fire-free interval analyses

5.2.2.1 Measures of central tendency

The Weibull Median Interval, Weibull Modal Interval, and Mean Fire Interval for each site indicated that fire occurred frequently across the study area. These measures of central tendency ranged from 4.6 to 7.9 years across all sites and percent-scarred classes (all fires, 10% scarred, and 25% scarred) (Table 5.3). As found in other fire-history studies (Grissino-Mayer *et al.* 2004), the Weibull Modal Interval < Weibull Median Interval < Median Fire Interval. However, in this study, the absolute differences were small. The relative homogeneity of these statistics among percent-scarred classes and among sites reflected the dominance of widespread, synchronous wildfire across the study area throughout the period of analysis (1700–1880). Although the Weibull Median Interval, Weibull Modal Interval, and Mean Fire Interval were similar among sites, all three measures of central tendency were slightly higher at the southernmost site (Bureau of Land Management) and were lowest at the northernmost site (Oso Ridge North).

5.2.2.2 Measures of range

The measures of range also varied among sites and among percent-scarred classes (Table 5.3). The minimum fire-free interval at all sites was one to two years in the all-fires class and one to three years in the 25% scarred class. The maximum fire-free interval ranged 10 to 14 years in the all-fires class and 10 to 22 years in the 25% scarred class. The longest fire-free interval (22 years in the 25% scarred class) occurred at the Bureau of Land Management site between 1773 and 1795. The Lower Exceedance Interval ranged from 2.4 to 3.6 years and the

Table 5.3 Descriptive statistics for each of four chronologies, determined for the period of analysis (1700–1880). Results included for (A) all fires (B) fires that scarred at least 10% of the samples, and (C) fires that scarred at least 25% of the samples.

A

Site	MEI[1] (yr)	MOI[2] (yr)	MFI[3] (yr)	SD[4] (yr)	CV[5]	MIN[6] (yr)	MAX[7] (yr)	LEI[8] (yr)	UEI[9] (yr)	MHI[10] (yr)
BLM	5.8	5.2	6.1	3.1	0.5	1	13	2.7	9.7	10.4
OSN	5.1	4.9	5.2	2.1	0.4	1	10	2.7	7.7	6.2
OSW	5.3	4.6	5.6	2.8	0.5	1	14	2.4	8.9	9.0
PCC	5.3	5.1	5.5	2.3	0.4	2	10	2.8	8.2	6.9

B

Site	MEI (yr)	MOI (yr)	MFI (yr)	SD (yr)	CV	MIN (yr)	MAX (yr)	LEI (yr)	UEI (yr)	MHI (yr)
BLM	6.5	6.1	6.6	2.8	0.4	2	13	3.4	9.9	9.5
OSN	5.4	5.1	5.5	2.4	0.4	1	10	2.8	8.4	7.2
OSW	6.2	5.8	6.4	2.8	0.4	2	14	3.2	9.7	9.3
PCC	5.9	5.8	6.0	2.4	0.4	3	11	3.3	8.8	7.5

C

Site	MEI (yr)	MOI (yr)	MFI (yr)	SD (yr)	CV	MIN (yr)	MAX (yr)	LEI (yr)	UEI (yr)	MHI (yr)
BLM	7.4	6.4	7.9	4.2	0.5	2	22	3.3	12.7	18.8
OSN	6.0	5.7	6.1	2.6	0.4	1	10	3.2	9.1	8.1
OSW	6.2	5.8	6.4	2.8	0.4	2	14	3.2	9.7	9.3
PCC	6.2	6.1	6.2	2.2	0.4	3	11	3.6	8.9	7.4

[1]MEI = Weibull Median Interval
[2]MOI = Weibull Modal Interval
[3]MFI = Mean Fire Interval
[4]SD = Standard Deviation
[5]CV = Coefficient of Variation
[6]MIN = Minimum Fire-Free Interval
[7]MAX = Maximum Fire-Free Interval
[8]LEI = Lower Exceedance Interval
[9]UEI = Upper Exceedance Interval
[10]MHI = Maximum Hazard Interval

Upper Exceedance Interval ranged from 7.7 to 12.7 years across sites and percent-scarred classes. The most variable measure of range was the Maximum Hazard Interval, which spanned 6.2 to 10.4 years in the all-fires class, and 7.4 to 18.8 years in the 25% scarred class. The Oso Ridge North chronology had the lowest Maximum Hazard Interval in all percent-scarred classes, while values were highest for the Bureau of Land Management chronology.

5.2.2.3 Measures of dispersion

The standard deviations of the fire-free intervals were lowest at Oso Ridge North and Paxton Springs Cinder Cone and ranged from 2.1 to 2.6 years across percent-scarred classes (Table 5.3). The standard deviations were only slightly higher at the Oso Ridge West and Bureau of Land Management sites and ranged from 2.8 to 4.2 years across percent-scarred classes. Comparisons between sites are more reliable with the coefficient of variation as this measure is normalized and is thus less affected by skewed data. Again, the Oso Ridge North and Paxton Spring Cinder Cone sites were characterized by the lowest values across percent-scarred classes while values were slightly higher at the other two sites.

5.2.2.4 Temporal analyses of fire frequency

The temporal analyses revealed that statistically significant differences existed in fire frequency between the periods 1700–1879 and 1880–2009 (Table 5.4). These periods correspond with the pre- and post-settlement periods, respectively. In the all-fires class, the Mean Fire Interval during the pre-settlement period ranged from 5.2 to 6.2 years among sites, while post-

Table 5.4 Results of the temporal analyses of differences in fire frequency between the periods 1700–1879 and 1880–2009 for individual sites and for all sites.

	BLM		OSN		OSW		PCC		All Sites	
	All Fires	25%	All Fires	25%	All Fires	25%	All Fires	25%	All Fires	25%
1700–1879 *n*-size	28	21	33	29	--	--	32	30	72	33
1880–2009 *n-size*	4	2	3	3	--	--	4	3	10	3
1700–1879 mean (yr)	6.2	8.0	5.2	5.9	--	--	5.3	5.7	2.5	5.2
1880–2009 mean (yr)	11.8	20.5	11.3	11.3	--	--	10.8	14.3	4.7	14.3
$\lvert t \rvert$-value	1.84	2.89	2.96	2.24	--	--	3.27	4.39	3.48	2.04
$P > t$	0.08	0.01**	0.01**	0.03*	--	--	0.00**	0.00**	0.00**	0.05*
1700–1879 variance	9.6	18.1	4.5	6.0	--	--	4.9	4.4	2.1	8.2
1880–2009 variance	61.6	4.5	22.3	22.3	--	--	16.9	8.3	7.6	134.3
F-value	2.06	22.80	1.28	1.03	--	--	1.04	2.82	1.17	4.96
$P > F$	0.26	0.33	0.53	0.77	--	--	0.81	0.59	0.93	0.03*
K-S d-statistic	0.50	0.95	0.67	0.67	--	--	0.69	1.00	0.47	0.67
$P > d$	0.35	0.07	0.17	0.18	--	--	0.07	0.01**	0.04*	0.17

*$P < 0.05$, **$P < 0.01$

settlement means ranged from 10.8 to 11.8 years. The means were significantly different at the 0.05 or 0.01 levels in all but one case (Bureau of Land Management, all-fires class). In contrast, the variances were typically statistically equal, with only one of the site/percent-scarred combinations resulting in significant differences (all sites, 25% scarred class). Likewise, the distributions of fire-free intervals among sites were generally statistically the same with the exception of the 25% scarred class for Paxton Springs Cinder Cone and the all-fires class for all sites. Temporal analyses for Oso Ridge West were not possible due to insufficient intervals during the post-settlement period.

No statistically significant differences in mean, variation, or distributions were found between fire-free intervals for the periods 1700–1799 and 1800–1880 (Table 5.5). However, the Mean Fire Intervals were slightly but consistently higher in the later period (Table 5.3). For example, the Mean Fire Intervals for the period 1700–1799 in the all-fires class ranged from 4.7 to 5.8 years while values for the period 1800–1880 ranged from 5.6 to 6.7 years. These subtle differences are apparent through visual inspection of the master fire-history charts for each site.

5.2.2.5 Spatial analyses of fire frequency

Spatial analyses revealed two statistically significant differences in Mean Fire Intervals. Individual site comparisons identified unequal Mean Fire Intervals between the Bureau of Land Management and Oso Ridge North sites in the 25% scarred class ($P < 0.05$; Table 5.6). The Bureau of Land Management site is the southernmost site at the foothills of the Zuni Mountains, while Oso Ridge North is the northernmost site. At a larger spatial scale, I also found a statistically significant difference between the Mean Fire Interval of my four sites and the Mean

Table 5.5 Results of the temporal analyses of differences in fire frequency between the periods 1700–1779 and 1800–1880 for individual sites and for all sites. Results are for the all-fires class.

	BLM	OSN	OSW	PCC	All Sites
1700–1799 n-size	16	20	17	18	41
1800–1880 n-size	12	12	14	14	31
1700–1799 mean (yr)	5.8	4.7	5.4	5.4	2.4
1800–1880 mean (yr)	6.7	5.9	5.6	5.7	2.6
$\|t\|$-value	1.11	1.05	0.60	0.15	0.02
$P > t$	0.28	0.30	0.55	0.88	0.98
1700–1799 variance	11.3	3.3	10.6	4.3	1.3
1800–1880 variance	7.9	6.3	5.7	7.3	3.3
F-value	2.34	2.44	2.31	1.57	1.56
$P > F$	0.16	0.09	0.14	0.40	0.20
K-S d-statistic	0.23	0.25	0.18	0.16	0.20
$P > d$	0.87	0.74	0.97	0.99	0.47

Table 5.6 Results of the spatial analyses of differences in fire frequency between individual sites and between sites in the Zuni Mountains and sites in El Malpais National Monument. The period of analysis is 1700–1880 and statistics all for the 25% scarred class.

	BLM vs. OSN	**BLM vs. OSW**	**BLM vs. PCC**	**OSN vs. OSW**	**OSN vs. PCC**	**OSW vs. PCC**	**ELMA vs. ZUNI**
$\lvert t \rvert$-value	1.65	1.38	1.50	0.39	0.48	0.13	2.79
$P > t$	0.02*	0.15	0.10	0.70	0.63	0.90	0.01**
F-value	1.05	1.24	2.07	1.28	1.95	1.69	1.27
$P >$ F	0.88	0.66	0.08	0.59	0.09	0.18	0.44
K-S d-statistic	0.18	0.21	0.26	0.07	0.08	0.11	0.25
$P > d$	0.84	0.64	0.40	1.00	1.00	0.99	0.06

*$P < 0.05$, **$P < 0.01$

Fire Interval of the four sites in El Malpais National Monument ($P < 0.01$). No statistically significant differences were found between variances and distributions for any of the spatial analyses I conducted.

5.2.3 Fire seasonality analyses

Fire seasonality analyses revealed that early-season fires were more common than late season fires during the entire period of analysis (1700–1880). Among sites, the percentage of early-season scars ranged from 55.0% to 62.3%. Large changes were observed in seasonality over time, as early-season scars became increasingly common (Figure 5.15). For example, during the period 1700 to 1799, the percentage of early-season scars ranged from 20.6% to 38.4% among sites, while the percentage of early-season scars ranged 71.3% to 89.2% among sites during the period 1800–1880. When all sites were combined and the entire period was broken down into smaller intervals ($n = 20$ years), it became apparent that the transition towards more frequent early-season fires began around 1780 and then leveled-out around 1820.

5.3 Fire-climate analyses

5.3.1 Superposed Epoch Analyses

Superposed Epoch Analyses revealed statistically significant relationships between several climate variables and wildfire during the period of analysis (1700–1880). The window of analysis extended ten years (beginning six years prior, and ending three years after a fire event). Results indicated that:

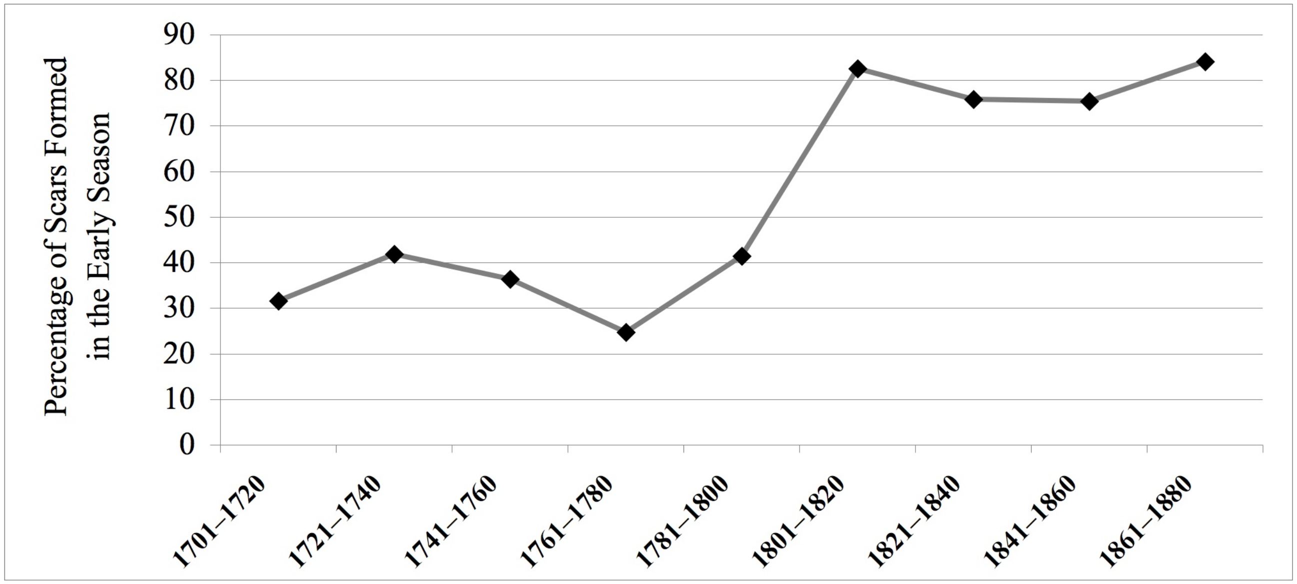

Figure 5.15 The percentage of scars formed in the early season in nine contiguous 20-year intervals over the period 1701–1880 at all sites.

- Above average precipitation occurred both one and three years prior to the fire event. Below average precipitation occurred during the year of the fire event ($P < 0.05$) (Figure 5.16).
- Above average PDSI values occurred one to three years prior to the fire event. Below average PDSI values occurred during the year of the fire event ($P < 0.05$) (Figure 5.17).
- Above average ENSO values occurred one year prior to the fire event. Below average ENSO values occurred during the year of the fire event ($P < 0.05$) (Figure 5.18).
- Average PDO conditions occurred throughout the ten-year window of analysis (Figure 5.19).

5.3.2 Chi-Square analysis

A chi-square goodness-of-fit test examined whether the distribution of widespread fire years among the four phase combinations of ENSO and PDO (+ENSO+ PDO, –ENSO–PDO, +ENSO–PDO and –ENSO+PDO) differed significantly from the distribution of all years among these phase combinations independent of fire activity (Figure 5.20; Table 5.7). Results indicated that no significant differences in widespread fire behavior occurred during unique phase combinations of ENSO and PDO. Although 43% of fires occurred when a negative ENSO corresponded with a negative PDO, this particular phase combination occurred more commonly than any other phase combination during the period of analysis (1700–1880; 37% of all years). Although absolute differences were apparent in the data, chi-square analysis indicated that these differences were not statistically significant.

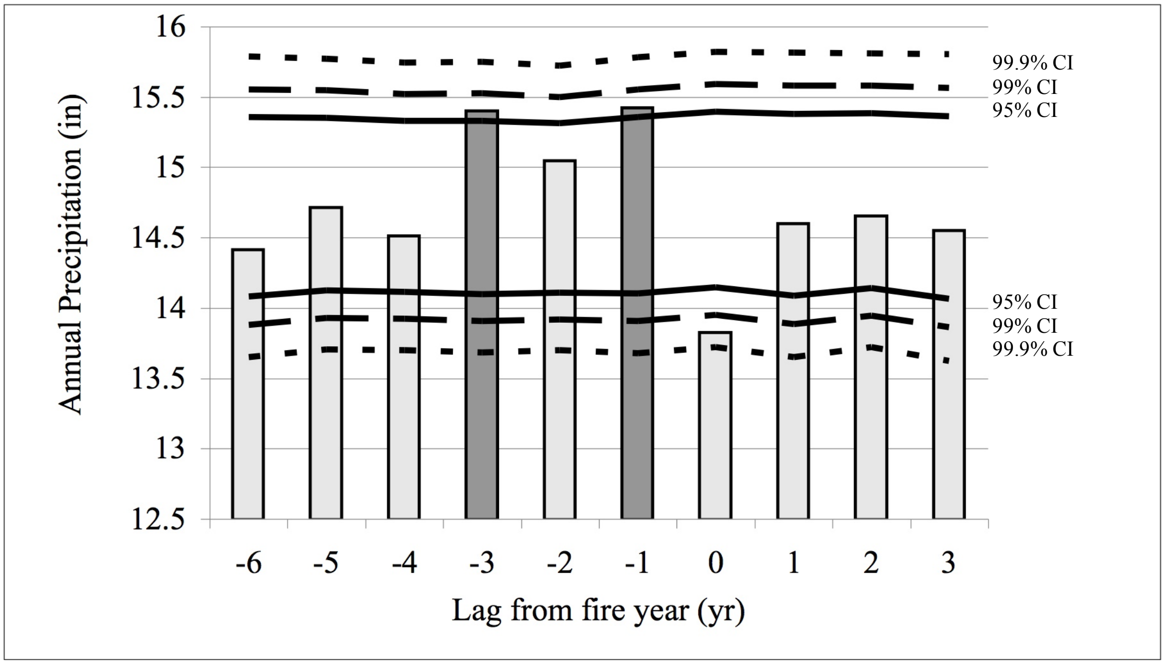

Figure 5.16 Superposed Epoch Analysis showing the relationship between annual precipitation and fire occurrence for the period 1700–1880. Darker bars indicate that results are significant.

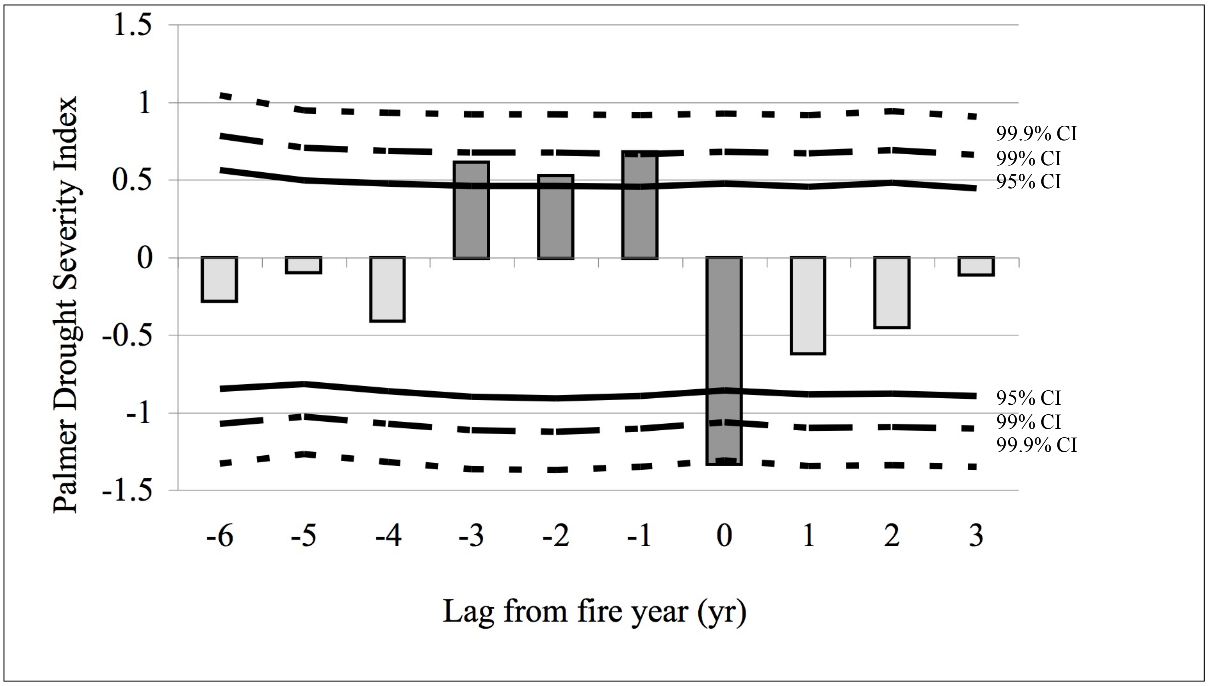

Figure 5.17 Superposed Epoch Analysis showing the relationship between PDSI and fire occurrence for the period 1700–1880. Darker bars indicate that results are significant.

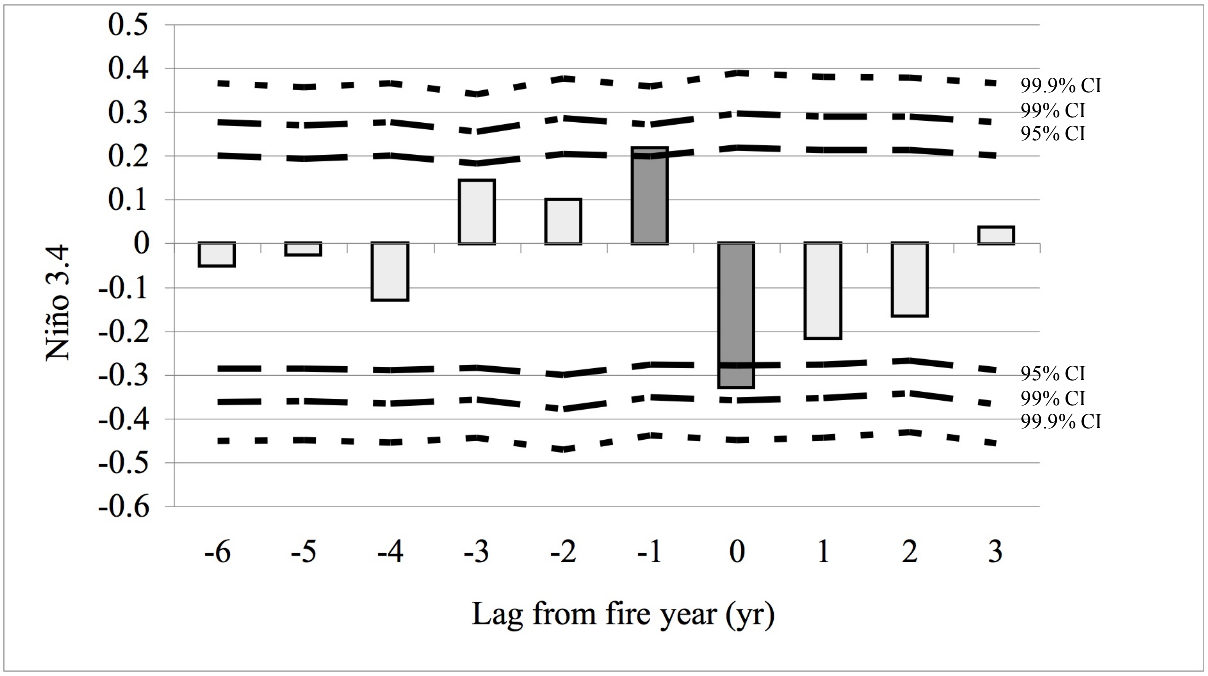

Figure 5.18 Superposed Epoch Analysis showing the relationship between ENSO and fire occurrence for the period 1700–1880. Darker bars indicate that results are significant.

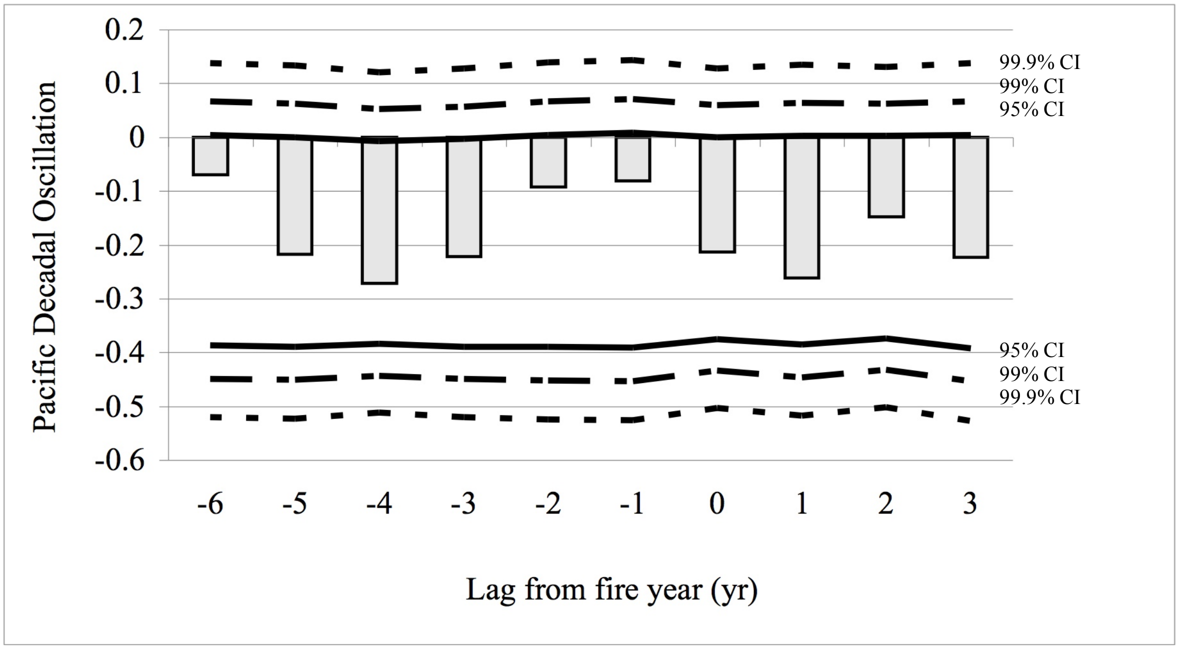

Figure 5.19 Superposed Epoch Analysis showing the relationship between PDO and fire occurrence for the period 1700–1880. Results are not significant at the desired confidence level (*P*<0.05).

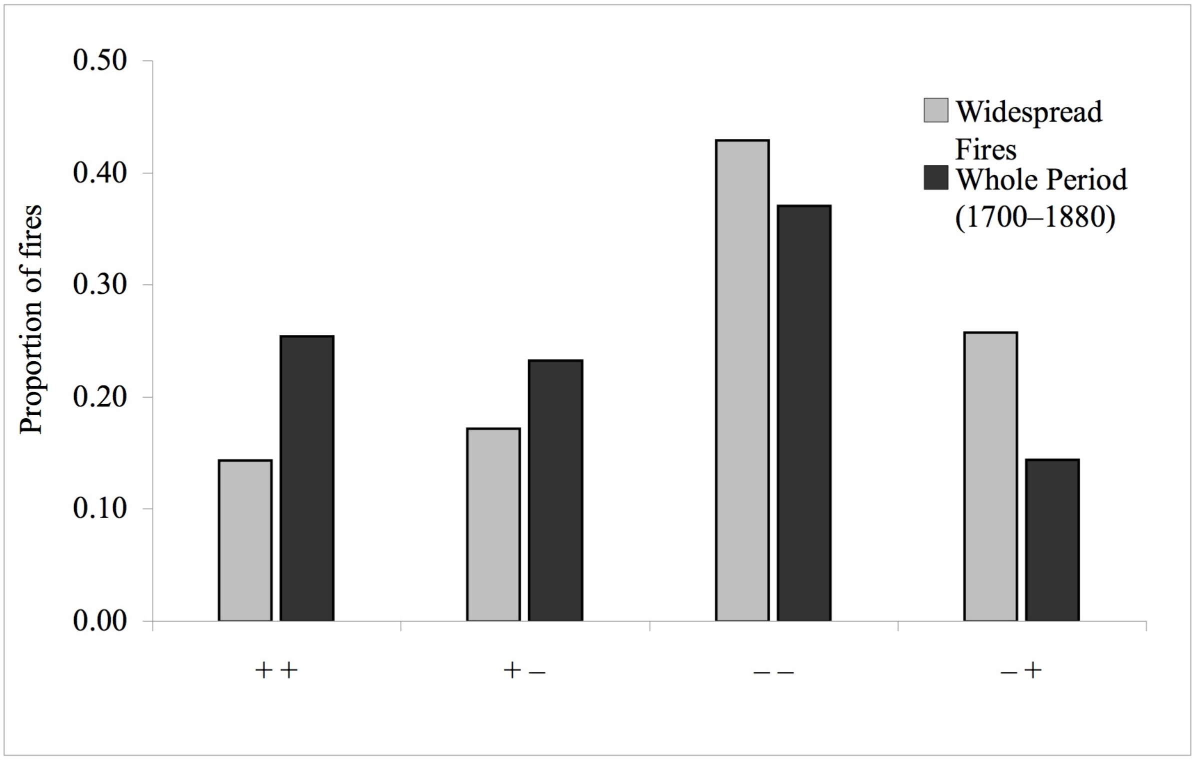

Figure 5.20 Proportion of widespread fires and of all years occurring during various phase combinations of ENSO and PDO. For each set of bars, the first symbol (+ or –) indicates the phase of ENSO and the second symbol (+ or –) indicates the phase of PDO.

Table 5.7 Chi-square analysis used to determine if differences in fire occurrence by phase combination were statistically significant. Results indicated that differences between observed and expected values were not statistically significant.

Phase Combination	Observed (*n*)	Expected (*n*)
+ ENSO + PDO	5	8.9
+ENSO –PDO	6	8.1
–ENSO +PDO	15	13.0
–ENSO –PDO	9	5.0

$\chi^2 = 5.721$ ($P = 0.13$)

5.4 The climate/tree-growth relationship

5.4.1 Correlation and response function analyses

Correlation and response function analyses of climate and tree growth provided complementary results. Correlation analyses indicated that tree growth was related to multiple climate variables during the period of analysis (1930–2008) (Figure 5.21). A positive and statistically significant correlation existed between precipitation and tree growth for the majority of the months analyzed. The highest consecutive correlations occurred in May and June of the current year (r = 0.26 and 0.34, $P < 0.05$). Correlations among PDSI and tree growth were also strong in May and June of the current year (r = 0.48 and 0.52, respectively, $P < 0.05$). In contrast, temperature correlated negatively with tree growth and results were significant only in a few of the months analyzed. Most notably, high temperatures in current year spring and summer months (May–July) negatively correlated with tree growth. Results of response function analyses complemented results of correlation analyses, although far fewer significant relationships were detected (Figure 5.22). As with correlation analyses, current year June precipitation and temperature were significant (r = –0.19 and 0.21, respectively, $P < 0.05$).

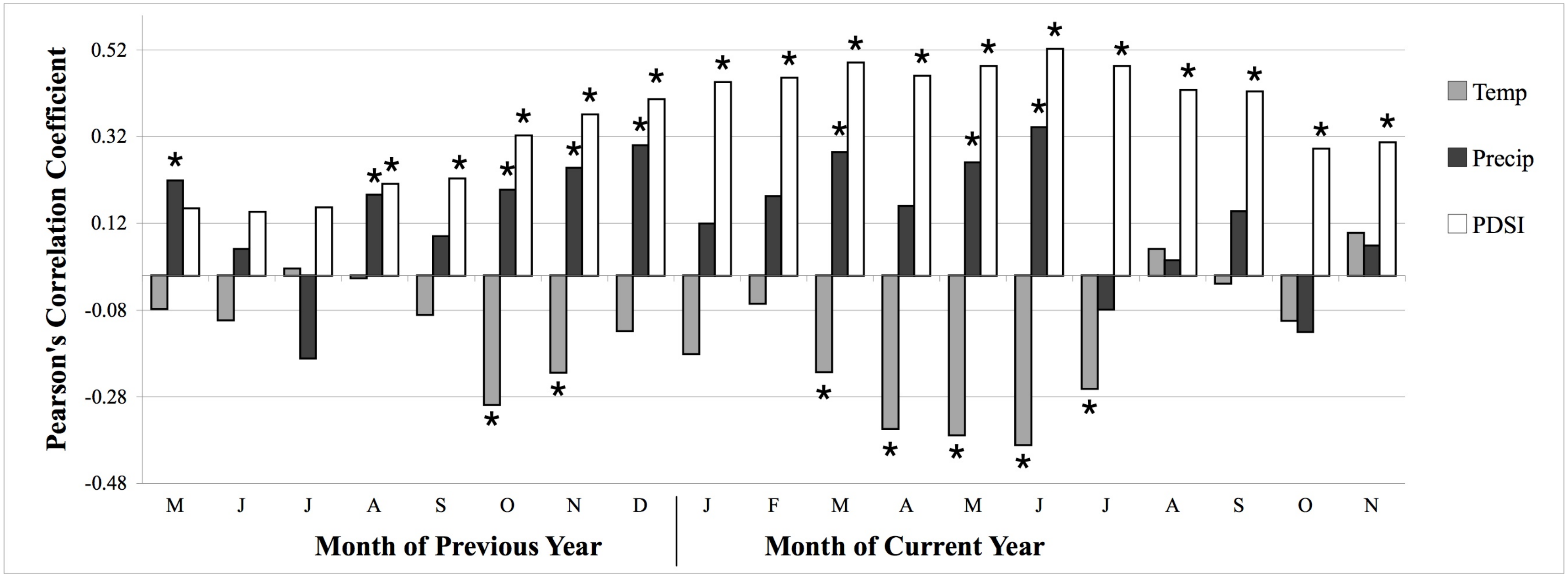

Figure 5.21 Correlation coefficients showing the relationship between the Paxton Springs Cinder Cone tree-ring chronology and monthly mean temperature, monthly total precipitation, and monthly PDSI from the previous May to the current November (1930–2008). Significant correlations ($P < 0.05$) are indicated by asterisks.

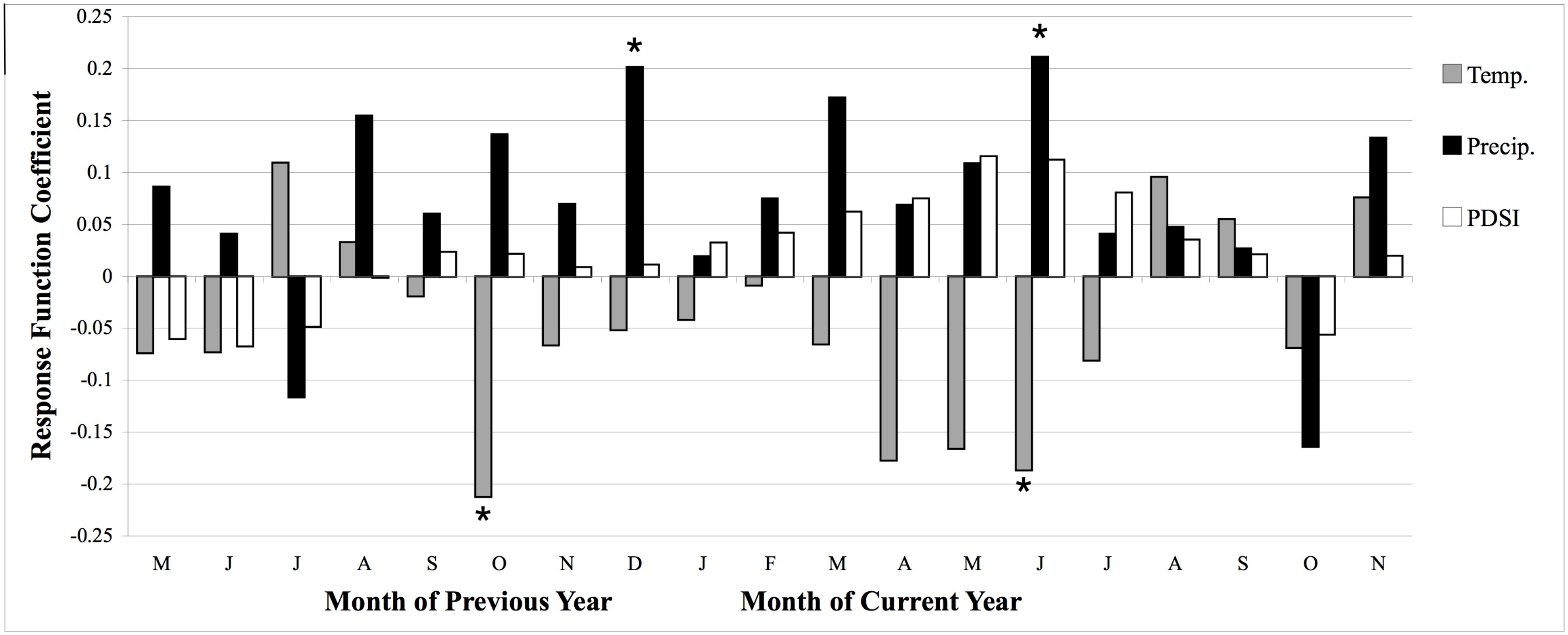

Figure 5.22 Response function coefficients showing the relationship between the Paxton Springs Cinder Cone tree-ring chronology and monthly mean temperature, monthly total precipitation, and monthly PDSI from the previous May to the current November (1930–2008). Significant relationships ($P < 0.05$) are indicated by asterisks.

CHAPTER SIX

6. DISCUSSION

In the Zuni Mountains and throughout the Southwest, forests dominated by ponderosa pine were historically open and experienced frequent, low-severity wildfires. In contrast, modern vegetation composition and structure promotes wildfires of moderate to high severity. Contemporary fires burn hotter, larger, and longer than historic fires, and often kill both young and mature trees. Changes in wildfire regimes in the Southwest are related to human disturbances including livestock grazing, timber harvesting, and fire suppression (Cooper 1960; Savage and Swetnam 1990; Covington and Moore 1994; Swetnam and Baisan 1996; Grissino-Mayer and Swetnam 1997; Moore *et al.* 1999; Allen *et al.* 2002).

The influences of land-use change on wildfire regimes may be compounded by human-induced climate change (Covington and Moore 1994; Grissino-Mayer *et al.* 2004; Westerling *et al.* 2006; Flannigan *et al.* 2009). Temperatures are on the rise globally, and many of the hottest years on record occurred since the late 1990s (IPCC 2007). In the southwestern United States, warmer temperatures are coincident with drier conditions, and most models predict that drought will continue to intensify in upcoming decades (Seager *et al.* 2007). Although the future of wildfire regimes in the Zuni Mountains and throughout the Southwest remains uncertain, it is likely that past land-use changes, in conjunction with a warming and drying climate, will drive ecosystem functioning further outside its historic range of variability. Land managers must take these issues into account as they plan how best to manage ponderosa pine forests of the American Southwest.

6.1 Historic wildfire regimes and implications for the future

The measures of central tendency I calculated for sites in the Zuni Mountains indicated that low-severity wildfires occurred frequently across the study area during the period of analysis (1700–1880). The Weibull Median Interval, Weibull Modal Interval, and Mean Fire Interval were similar among sites and collectively suggested that fires that scarred two or more trees occurred on average once every five to six years. Although differences were minor, fires tended to occur somewhat less frequently at the southernmost site (Bureau of Land Management) and somewhat more frequently at the sites along Oso Ridge (Oso Ridge North and Oso Ridge West). Widespread fires that were recorded on at least 25% of all sampled trees were also common and occurred every six to eight years. In stark contrast to historic conditions, fires are now essentially absent from Zuni Mountain forests. The most recent fire in the master chronology took place in 1927. Although change is an inherent part of any ecosystem (Holling 1973; Morgan *et al.* 1994; Veblen and Donnegan 2006), the current wildfire regime is operating well outside the historic range of variability, and has been strongly influenced by human disturbances.

My findings on pre-settlement fire frequency in the Zuni Mountains are reasonable when compared to other fire-history studies from the Southwest (Table 6.1). For example, Swetnam and Baisan (1996) conducted a comprehensive study of over 60 sites in Arizona, New Mexico, Texas, and Sonora, Mexico. They determined that the Weibull Median Interval at each site ranged approximately 2 to 17 years for the all-fires class. In terms of more local studies, my findings are also consistent with those of Grissino-Mayer (1995). He found that in El Malpais National Monument, the Weibull Median Interval for all fires ranged from approximately 6 to 12 years. Although the range of my results is narrower than that of previous studies, less variability

Table 6.1 Fire-history statistics for all reconstructed fires as determined by three separate studies for the American Southwest.

	The Zuni Mountains	**El Malpais National Monument**[1]	**The Southwest**[2]
Number of Sites	4	9	63
Period of Analysis	1700–1880	Varied by site (*see* Appendix 3)	1700–1900
Weibull Median Interval (yr)	5.1–5.8	5.1–11.7	1.7–16.8
Minimum Fire-Free Interval (yr)	1–2	1–3	1–4
Maximum Fire-Free Interval (yr)	10–14	12–55	9–89
Maximum Hazard Interval (yr)	6–10	16–529	--

[1] Grissino-Mayer (1995)
[2] Swetnam and Baisan (1996)

was expected given the smaller spatial scale of my study (fewer sites, less total area).

Maximum Hazard Intervals for sites in the Zuni Mountains were shorter than expected, and indicated that historically, fire became exceedingly probably after only about a decade. In contrast, in El Malpais National Monument, Grissino-Mayer (1995) determined that the Maximum Hazard Interval for many sites was significantly longer, ranging between 16 and 529 years. The difference in the Maximum Hazard Intervals for sites in the Zuni Mountains compared to those in the neighboring National Monument may have resulted from dissimilarities in fuel interconnectivity. In El Malpais National Monument, lava flows and other volcanic features such as cinder cones are common and likely served as barriers to fire spread. In contrast, large, natural fuel breaks are uncommon in the Zuni Mountains.

The relatively short Maximum Hazard Intervals for fire regimes of the Zuni Mountains indicated that the present fire hazard is extremely high. Fire has been absent in the study area for approximately 80 years, vastly exceeding historic fire-free intervals. The absence of fire has provided the opportunity for fuels to accumulate, and has promoted higher stand densities. These ecological conditions allow wildfire to spread into the canopy via ladder fuels, thereby facilitating high-severity fire (Allen *et al.* 2002; Schoennagel *et al.* 2004). Although to my knowledge large, stand-replacing fire has not yet occurred in the Zuni Mountains, the future likelihood of such an event is extremely high.

6.2 Native Americans vs. lightning as the ignition source of historic wildfires

The fire-history methods used in this research revealed that fires occurred frequently across the study area between 1700 and 1880. However, data collected are limited in the sense that the ignition source of each fire cannot be determined. Despite this limitation, I made the assumption that historic wildfires in the study area were ignited primarily by lightning, rather than by humans. The Southwest experiences extremely high lightning activity, especially around the time of the summer monsoon (Barrows 1978; Watson *et al.* 1994; Allen 2002). A period of low rainfall and warm temperatures prior to the advent of the monsoon desiccates fuels and creates a high fire hazard (Swetnam and Betancourt 1998; Allen 2002). Thus while Native Americans might have ignited some fires, southwestern climate conditions in the absence of human ignitions can explain the historic occurrence of frequent, low-severity wildfire.

As a further consideration, ponderosa pine is a highly fire-adapted species. Ponderosa pine has been present in the Southwest for hundreds of thousands of years (Moir *et al.* 1997), and many current adaptations of the genus (*Pinus*) may be related to its long-term coexistence with fire (Agee 1998). Thick, corky bark, the frequent shedding of needles, and the production of pitch following fire injury are just a few examples of how ponderosa pine is well-adapted to fire (Arno and Allison-Bunnell 2002). It is likely that long before human populations were of a significant size in the Southwest, lighting-ignited fires occurred frequently and played an important role in the evolution of ponderosa pine.

6.3 The influence of anthropogenic disturbances on fire regimes

Although Native Americans likely played only a small role in shaping historic wildfire regimes of the Zuni Mountains, the influence of Euro-American settlers was undoubtedly profound. Fire frequency declined suddenly in the study area in the late 19th century, and very few fires occurred post–1880. Although major changes in fire frequency in western forests can be attributed to climatic changes (Westerling *et al.* 2006), the decline in fire frequency in my study area likely resulted from widespread livestock grazing, which was followed by other anthropogenic disturbances including timber harvesting and fire suppression.

The initial decrease in fire frequency in the Zuni Mountains corresponded with the advent of sheepherding. The Atlantic & Pacific Railroad arrived to the area in 1881 and allowed sheepherding operations to expand rapidly throughout the Zuni Mountains and the area that is now El Malpais National Monument (Robinson 1994; Magnum 1997). By consuming fine fuels, sheep and other livestock prevented fire ignition and spread (Leopold 1924; Cooper 1960; Savage and Swetnam 1990; Touchan *et al.* 1995; Grissino-Mayer and Swetnam 1997). Land managers have long been aware of how livestock grazing can effectively inhibit fire. In the early 20th century, the U.S. Forest Service intentionally used grazers to reduce wildfire occurrence (Leopold 1924). In some areas of the Southwest, livestock grazing was introduced significantly earlier or later, and in these areas a decline in fire frequency did not occur *ca.* 1880, but instead took place simultaneously with the introduction of grazing. In areas known to be isolated from livestock grazing, fire frequency did not decline at all in the late 19th century (Savage and Swetnam 1990; Grissino-Mayer and Swetnam 1997; Touchan *et al.* 1995; Lewis 2003).

Although sheepherding was most likely the initial cause of decreased fire frequency in the Zuni Mountains, other anthropogenic disturbances were also important and further altered ecological patterns and processes. Logging operations began in 1890 with the construction of the Zuni Mountain Railway and resulted in intense deforestation (Myrick 1990; Magnum 1997). By removing most or all mature trees, logging throughout the Southwest promoted rapid and widespread regeneration of young pines. Ultimately, these post-logging forest conditions are conducive to infrequent, high-severity fire, rather than frequent, low-severity fire (Covington 2003).

Fire suppression is another anthropogenic disturbance that altered wildfire regimes of the Zuni Mountains. Although fire suppression was a policy adapted by the U.S. Forest Service in the early 20th century, it was not until after World War II that fire suppression efforts became effective enough to significantly disrupt wildfire occurrence (Covington and Moore 1994; Grissino-Mayer and Swetnam 1997; Swetnam and Baisan 2003). Under the Smoky Bear campaign, fire was viewed as an enemy to both society and nature (Dellasala *et al.* 2004). Fire suppression promoted seedling establishment, thus further increasing stand density and excluding fine fuels (Cooper 1960; Savage and Swetnam 1990; Covington and Moore 1994; Grissino-Mayer 1995). Fire suppression is often identified as the primary cause of fire exclusion in the United States, but in the Zuni Mountains and in other parts of the Southwest, three major disturbances (sheepherding, timber harvesting, and fire suppression) together altered wildfire regimes.

6.4 Climate-wildfire relationships

During the period 1700 to 1880, climatic variability strongly influenced fire occurrence in the Zuni Mountains. Superposed Epoch Analyses indicated that significant relationships existed between wildfire activity and precipitation, as well as other closely related climate indices, such as ENSO and PDSI. Wetter conditions occurred one to three years prior to the fire event, while drier conditions occurred during the fire year. A likely explanation for this pattern is that antecedent moister conditions promoted the accumulation of fine fuels. Drought during the fire year then desiccated fuels for burning. Similar patterns were identified for the nearby El Malpais National Monument (Grissino-Mayer and Swetnam 2000). At an even larger spatial scale, studies conducted in other open, ponderosa pine forests also showed that antecedent moister conditions preceded drought during the fire year (Baisan and Swetnam 1990; Swetnam and Betancourt 1998; Grissino-Mayer and Swetnam 2000; Grissino-Mayer *et al.* 2004; Sherriff and Veblen 2008).

In contrast to the case of short-term precipitation patterns and their related indices (PDSI and ENSO), no statistically significant relationships were identified among phases of PDO and fire occurrence during the period of analysis (1700–1880). In addition, phase combinations of ENSO and PDO appeared unimportant in explaining wildfire occurrence. These findings suggested that the Southwest was historically less affected by PDO and by ENSO/PDO phase combinations than other regions of the United States. Previous research in the Rocky Mountains lends credence to this explanation. Significant relationships between PDO and wildfire were identified in subalpine forests (Schoennagel *et al.* 2005, 2007; Sherriff and Veblen 2008), but not in lower-elevation ponderosa pine forests (Sherriff and Veblen 2008). Dissimilarity between these forest types was expected given differences in forest composition and structure, and the influences of those differences on wildfire regimes. Higher elevation forests tend to be denser and experience large, high-severity wildfires during periods of prolonged drought. In contrast, lower elevation forests were more open and experienced low-severity wildfires driven by interannual wet/dry-lagging patterns. Because fires in open, ponderosa pine forests depended on *short-term* variability in precipitation, climate patterns related to precipitation, PDSI, and ENSO, rather than longer-term variability related to PDO, were historically most influential to fire occurrence in the Zuni Mountains.

Although my research suggested that PDO and ENSO/PDO phase combinations were not significantly related to fire behavior in the Zuni Mountains, it is a possibility that the spatial scale of my study was too small to uncover these broadscale patterns. Most fire-climate studies that examine relationships between wildfire and decadal to multidecadal climatic variability draw on a broad network of fire-history sites (*e.g.* Kitzberger *et al.* 2007; Heyerdahl *et al.* 2008). Thus more research may be needed to validate my findings.

6.5 Fire seasonality

In addition to changes in fire frequency, I also observed changes in fire seasonality across the study area. During the period 1700 to 1880, early-season fires became increasingly common until, by 1880, over 80% of observed fire scars dated as early season. In contrast, from 1700 to 1780, less than 45% of fires occurred in the early season. Grissino-Mayer and Swetnam (2000) argued that changes in fire seasonality might be related to changes in the precipitation regime driven by variability in ENSO and in the summer monsoon. They suggested that more frequent El Niño events, coupled with decreased rainfall during the summer monsoon, could explain higher frequency in late-season fires prior to 1800. Given similarities in fire seasonality between the National Monument and the Zuni Mountains, it is likely that the explanation provided by Grissino-Mayer and Swetnam (2000) also applies to patterns that I observed across my study area.

6.6 Comparison of fire regimes among individual sites in the Zuni Mountains, and between the Zuni Mountains and El Malpais National Monument

The fire chronologies of my four sites were relatively similar. From 1700 to 1880, the Weibull Median Interval ranged from five to seven years among sites and percent-scarred classes. Spatial analyses of fire frequency revealed that differences in fire-free intervals among sites were not statistically significant. Fires were often synchronous among sites, and across the study area, 25% of all fires identified occurred at a minimum of three sites. Fire may have ignited independently at these sites due to climate-forcing conditions. This explanation is reasonable given that lightning activity is high in the Southwest (Weaver 1951; Cooper 1960; Barrows 1978; Watson *et al.* 1994; Allen 2002; Barrett *et al.* 2005). Alternatively, fire may have ignited at one or more sites and then spread into the surrounding areas. This hypothesis is also highly probable as few or no large fuel breaks (*e.g.* roads, rivers, lava flows) were historically present that would have obstructed fire spread. Most likely, both explanations are correct. Fires sometimes ignited independently at two or more sites, and at other times, fire may have ignited at one site and spread into adjacent areas. Although my research did not enable me to say definitively that the fuels and fire regimes of the Zuni Mountains were interconnected, findings suggested that fires were able to spread across the landscape.

I also compared the fire regimes of the Zuni Mountains to those of El Malpais National Monument. Analysis of fire frequency at my four sites compared to that of the four most proximal sites in the National Monument (Cerro Bandera East, La Marchanita, Candelaria, Cerro Bandera North) revealed that fire-free intervals in the Zuni Mountains were statistically different from those of El Malpais National Monument. This finding was reasonable given dissimilarities in elevation, vegetation, and geology between these two areas. El Malpais National Monument is slightly lower in elevation and is covered in lava flows. In many cases, trees are growing directly on the lava, with little or no soil. In contrast, the Zuni Mountains are higher in elevation. Soils are more developed and forests are denser and more mesic. Although fire frequencies were statistically different, it is important to note that in absolute terms these differences were minor, and that the wildfire regimes of the Zuni Mountains and El Malpais National Monument shared many common characteristics. For example, many widespread fires that occurred in the Zuni Mountains also occurred in the National Monument (*e.g.* 1748, 1795, 1824, 1861, and 1880). As in the Zuni Mountains, these synchronous fires may have ignited simultaneously, or may have spread across large areas.

6.7 Inferences about climate-wildfire relationships and overall forest health in the face of climate change

Consensus exists among the scientific community that human-induced climate change is dramatically altering climate conditions at a global scale (IPCC 2007). In the American Southwest, changes in temperature and precipitation patterns may profoundly affect ecosystem functioning. Seager *et al.* (2007) examined numerous climate models for the Southwest and determined that forecasted increases in temperature will be accompanied by substantially more arid conditions during the 21st century. These findings support those of the IPCC (2007). Typical climatic conditions are predicted to resemble major historic droughts such as the Dust Bowl and the 1950s drought. Seager *et al.* also predicted that ENSO will continue to drive fluctuations in precipitation, and that intense La Niña events will produce exceptionally severe drought conditions. These changes in temperature and precipitation patterns will likely result in changes in wildfire behavior in the Zuni Mountains and surrounding areas. Although historically, wet/dry-lagging patterns promoted low-severity wildfire, this relationship has been disrupted, and future climate-fire relationships remain uncertain. Previous research has suggested that wildfires in the West will continue to increase in size and severity under climate change scenarios (Westerling *et al.* 2006). It is thus possible that in the future, wildfire activity will increase in the Zuni Mountains. Given unprecedented fuel loadings, future fires are more likely to be high-severity.

In addition to altering climate-wildfire relationships, climate change might affect forest health in the Zuni Mountains in other ways. My analyses of the climate/tree-growth relationship revealed that wetter conditions were associated with increased tree growth, while drier conditions were associated with decreased growth, and abundant precipitation in the previous winter and current summer was strongly correlated to increased ring width in any given year. In contrast, the relationship between mean monthly temperature and tree growth was negative, with above average temperatures associated with reduced growth. Forecasted hotter, drier conditions in the Southwest may therefore inhibit tree growth in the Zuni Mountains. Increased forest dieback is also a possibility. Climate-related forest dieback has already been identified in other forests of New Mexico. Allen (2007) explored the relationship between climate conditions and forest health in northern New Mexico and identified severe drought and atypically high temperatures as key factors in driving widespread forest dieback. These climatic stresses were especially detrimental because of an existing beetle outbreak. A similar outcome for the Zuni Mountains might be expected given existing climate/tree-growth relationships.

6.8 Suggestions for land managers in the Zuni Mountains and throughout the Southwest

Southwestern ponderosa pine forests are often managed to reduce the costs and hazards associated with high-severity wildfire. The consensus from fire-history research is that crown fires did not occur prior to Euro-American settlement in these forests, or were at least extremely uncommon. Human disturbances have led to unprecedented fuel accumulation and stand densities, and have dramatically increased the likelihood of high-severity fire (Cooper 1960; Covington and Moore 1994; Grissino-Mayer and Swetnam 1997; Allen 2002). Fires are costly to suppress, and federal expenditures for fire fighting often exceed $1.6 billion per year (Whitlock 2004). A proposed solution to reducing fire suppression expenditures is restoration (Covington *et al.* 1997; Moore *et al.* 1999; Allen *et al.* 2002; Romme *et al.* 2003; Friederici 2003). Although restoration can be costly, research has indicated that a well-managed project can be economically viable (Lynch *et al.* 2000; Snider *et al*. 2006).

But is complete restoration possible and/or desired in southwestern ponderosa pine forests? Can we return forests to natural conditions, and just what is natural? Increasingly, researchers acknowledge problems in management goals that aim to restore ecological systems to a static, pre-settlement state, as ecosystems are understood to be continuously changing over time and space (Holling 1973; Pickett and Parker 1994; Morgan *et al.* 1994; Veblen and Donnegan 2006). Also recognized is that the concept of restoration is inherently subjective because of its requirement that a target ecosystem be identified. Although land managers often choose to restore ecological conditions directly prior to Euro-American settlement, this decision involves a judgment that this period is more desirable than other periods (Davis 2000; Choi 2004, 2007). Moreover, in some environments, complete restoration may simply not be feasible (Choi 2004, 2007; Westerling *et al.* 2006; Williams and Jackson 2007; Keith *et al.* 2009). The development of “non-analogous” ecological communities is increasingly discussed as an argument against traditional restoration goals (Figure 6.1). Non-analogous communities are new communities that differ substantially in species composition from current or pre-existing communities (Keith *et al.* 2009). The emergence of these unprecedented communities is attributed to human-induced climate change (Choi 2007; Williams and Jackson 2007; Keith *et al.* 2009) and to the effects of post-settlement disturbances (Wali 1999; Choi 2004; 2007). In the Zuni Mountains, a warmer, drier climate in conjunction with a long history of intense anthropogenic disturbances may make traditional restoration goals (*i.e.* full return to pre-settlement patterns) unrealistic.

The inability to restore as conventionally defined does not imply that landscapes should not be managed. Rather, what is required is an approach that acknowledges that forest ecosystems are highly dynamic (Holling and Meffe 1996; Moore *et al.* 1999; Allen *et al.* 2002; Veblen and Donnegan 2006). These ideas are consistent with contemporary ecosystem management practices (Landres *et al.* 1999; Veblen and Donnegan 2006). Rather than attempting to recreate a static, past environment, contemporary ecosystem management practices are flexible and acknowledge the role that both human and natural processes play in determining forest dynamics. They use the historic range of variability of past ecosystem patterns and processes as a general guide for management, rather than as a strict mandate.

My research has provided a picture of the historic range of variability of wildfire regimes of the Zuni Mountains. Low-severity wildfire occurred frequently across the study area during the period 1700 to 1880, although differences in fire regimes were evident among the four sites. It is likely that over larger temporal and/or spatial scales, wildfire regimes were even more variable than what was captured by this study. Looking forward, climatic conditions may

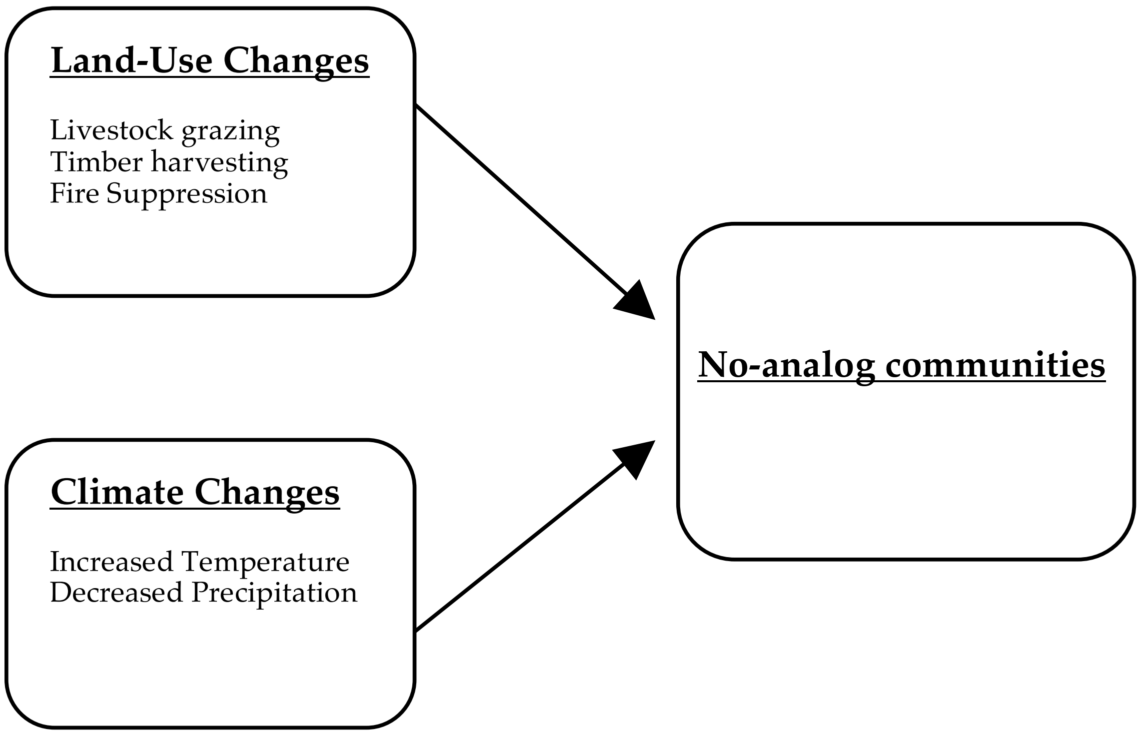

Figure 6.1 Schematic of factors that may contribute to the formation of no-analog communities in the American Southwest.

promote ecosystem conditions that were historically unprecedented in the Zuni Mountains. Land managers may choose to reintroduce a low-severity wildfire regime to the area, but must take into consideration the implications of past land-use and human-induced climate change.

CHAPTER SEVEN

7. CONCLUSION

7.1 Major conclusions

Fire-history methods that relied on tree rings enabled a high-resolution reconstruction of the temporal and spatial characteristics of historic wildfire regimes of the Zuni Mountains. The fire-scarred samples came exclusively from ponderosa pine, a species that lends itself well to this type of research (Arno and Sneck 1977; Dieterich and Swetnam 1984). In all, I dated 806 fire scars on 75 specimens of ponderosa pine from four sites. Missing and false rings occasionally challenged the dating process, but visual crossdating along with COFECHA software output confirmed accurate dating of all annual rings. Fire scars were well preserved and followed clear paths within ring boundaries. I was able to assign seasonality to nearly 90% of the scars within the period of analysis. Sample depth was strong for each chronology, at least as far back as 1700, and these ecosystems were relatively undisturbed by Euro-American settlers until around 1880. Thus, robust analysis of climate-wildfire relationships in the absence of human land-use change was possible for the period 1700 to 1880.

7.1.1 Research objective #1

Characterize historic (1700–1880) wildfire regimes.

Fire-history results indicated that low-severity wildfires occurred frequently in the Zuni Mountains. The Weibull Median Interval, Weibull Modal Interval, and Mean Fire Interval were similar among the four study sites and suggested that fires that scarred two or more trees occurred on average once every five to six years. Widespread fires that were recorded on at least 25% of all sampled trees were also common, and occurred every six to eight years. Fires did not occur at even intervals, but instead fire-free intervals varied in length during the period of analysis. Fires in consecutive years occurred at three of the four sites, yet one or more fire-free interval of at least a decade was also identified at all sites in all percent-scarred classes. Many samples contained more than ten fire scars, further indicating that historic wildfire regimes were characterized by frequent low-severity fire.

7.1.2 Research objective #2

Determine the influence of anthropogenic disturbances on wildfire regimes.

Native Americans likely had a minimal influence on wildfire regimes of the Zuni Mountains. The most likely ignition source of historic wildfires was lightning. The climate of the Southwest is conducive to frequent wildfire, with severe thunderstorms occurring during the summer monsoon (Barrows 1978; Watson *et al.* 1994; Allen 2002). A period of low rainfall and warm temperatures prior to the advent of the monsoon desiccates fuels, and increases their flammability (Swetnam and Betancourt 1998; Allen 2002). While Native Americans likely ignited some fires, southwestern climate conditions in the absence of human ignitions can explain the historic occurrence of frequent, low-severity wildfire.

Wildfire regimes of the Zuni Mountains were strongly influenced by land-use changes enacted by Euro-American settlers. Sheepherding was the first major anthropogenic disturbance to affect Zuni Mountain forests. The Atlantic & Pacific Railroad arrived to the area in 1881 and allowed sheepherding to expand rapidly throughout the mountains and into the area that is now

El Malpais National Monument (Magnum 1997). Sheepherding inhibited wildfire by removing fine fuels. Later, intensive logging removed most or all adult trees and allowed for rapid and widespread regeneration of young pines. The vast majority of Zuni Mountain forests were harvested during the early 1900s (Myrick 1990; Magnum 1997). Finally, fire suppression policies enforced by the U.S. Forest Service virtually eradicated wildfire occurrence (Cooper 1960; Covington and Moore 1994; Grissino-Mayer and Swetnam 1997; Allen *et al.* 2002). Together, these three disturbances (sheepherding, timber harvesting, and fire suppression) led to the formation of dense, “doghair” thickets that presently characterize ponderosa pine forests in the Zuni Mountains. While fires were previously limited to the grassy understory, abundant ladder fuels and high stand densities now increase the likelihood of high-severity wildfire.

7.1.3 Research objective #3

Examine historic (1700–1880) climate-wildfire relationships.

Climate strongly influenced wildfire occurrence across the study area. Results from Superposed Epoch Analyses indicated that significant relationships existed between wildfire activity and precipitation, and other closely related climate indices including ENSO and PDSI. Wetter conditions occurred one to three years prior to fire, while drier conditions occurred during the fire year. Antecedent moister conditions were important because they allowed fine fuels to accumulate. Drought during the fire year then desiccated fuels for burning. Similar patterns were identified for the nearby El Malpais National Monument (Grissino-Mayer and Swetnam 2000) and other parts of the West (Baisan and Swetnam 1990; Swetnam and Betancourt 1998; Grissino-Mayer *et al.* 2004; Sherriff and Veblen 2008).

In contrast to short-term precipitation patterns and related indices (PDSI and ENSO), I found no statistically significant relationships between phases of PDO and fire occurrence during the period 1700 to 1880. In addition, phase combinations of ENSO and PDO appeared not to have influenced historic wildfire behavior. It may be that ponderosa pine forests of the Southwest were historically less affected by PDO and by ENSO/PDO phase combinations than other regions of the United States. Previous research in the Rocky Mountains supports this explanation. Significant relationships between PDO and wildfire were identified in high-elevation subalpine forests (Schoennagel *et al*. 2005, 2007; Sherriff and Veblen 2008), but not in low-elevation, ponderosa pine forests (Sherriff and Veblen 2008). Because short-term, wet/dry-lagging patterns promoted fires in open, ponderosa pine forests of the Zuni Mountains, interannual climatic variability, rather than longer-term climatic variability, was historically most influential to fire activity.

An additional climate-wildfire pattern I observed was a shift towards more frequent early-season fires across the study area during the period of analysis (1700–1880). Early-season fires became increasingly common over time, and by 1880, over 80% of fire scars that were observed dated as early season. This shift in fire seasonality has been identified in other parts of the Southwest (Grissino-Mayer and Swetnam 2000; Lewis 2003). As suggested by Grissino-Mayer and Swetnam (2000), the shift in seasonality might be related to changes in the precipitation regime driven by variability in ENSO and in the summer monsoon. More frequent El Niño events, along with decreased rainfall during the monsoon, might explain the more frequent occurrence of late-season fires prior to 1800.

7.1.4 Research objective #4

Compare wildfire regimes of each of the four sites in the Zuni Mountains in terms of fire frequency and synchrony and also compare wildfire regimes of the Zuni Mountains to those of the adjacent El Malpais National Monument.

Wildfire regimes among my four sites shared many characteristics. The Weibull Median Interval, Weibull Modal Interval, and Mean Fire Interval were similar among sites and collectively suggested that fires that scarred two or more trees occurred on average once every five to six years. Widespread fires were also common, and across the study area, 25% of all fires identified occurred at a minimum of three sites. Fire may have ignited independently at these sites due to climate-forcing conditions, or fire may have ignited at one or more sites and then spread into the surrounding areas. Although wildfire regimes across the Zuni Mountains were similar, some differences existed among the four sites. For example, sites differed in the timing of the late 1800s decrease in fire frequency. The railroad did not enter the area until 1881 (Myrick 1990; Magnum 1997), but small sheepherding operations may have affected portions of the Zuni Mountains earlier.

The fire regimes of the Zuni Mountains were also similar to those of El Malpais National Monument. Spatial analysis revealed that the fire-history sites in the Zuni Mountains were characterized by fire-free intervals that were statistically unique from those of El Malpais National Monument, but many commonalities in wildfire regimes were identified. Low-severity fires occurred frequently in both areas. Furthermore, numerous widespread fires that occurred at multiple sites in the Zuni Mountains also burned areas of El Malpais National Monument.

7.1.5 Research objective #5

Make inferences about climate-wildfire relationships and overall forest health in the face of climate change.

Southwestern forest managers must prepare for an increased likelihood of high-severity wildfire. Historically, Zuni Mountain forests experienced frequent, low-severity wildfire. Wildfire occurrence was related to short-term variability in precipitation. Today, wildfire is essentially absent from the Zuni Mountains, and forest composition and structure has changed radically. Rather than open stands of ponderosa pine with a well-developed understory, current stands are dense and contain more fire-intolerant species. In the absence of fire, fuels have accumulated beyond historic precedent, and the Maximum Hazard Intervals calculated for each site indicated that fire is long overdue. Because past climate-wildfire relationships are no longer operative, it is difficult to predict what climatic conditions will promote fire in the future. However, when fire does occur, it is much more likely to be catastrophic.

Future changes in southwestern climate may affect tree growth and mortality in the Zuni Mountains. My analyses of the climate/tree-growth relationship revealed that several climate variables were associated with tree growth in the study area. The most obvious pattern was that wetter conditions were associated with increased growth while drier conditions were associated with decreased growth during the period of analysis (1930–2008). The correlations between abundant precipitation in the previous winter and current summer were especially strong. In contrast, the relationship between temperature and tree-growth was negative, with above average temperatures associated with reduced growth. Earlier work by Allen (2007) identified high temperature and drought as factors related to forest dieback in New Mexico. If past and current climate/tree-growth relationships apply to the future, warming temperatures accompanied by decreased precipitation might limit annual growth in the Zuni Mountains, and eventually result in widespread, forest dieback.

7.1.6 Research objective #6

Make suggestions for land managers in the Zuni Mountain area and throughout the Southwest.

Land managers must prepare for an increased likelihood of high-severity wildfire in the Zuni Mountains. Fuel management strategies that aim to reduce ladder fuels through mechanical thinning and prescribed fire might help inhibit the occurrence of catastrophic fire by promoting a lower-severity wildfire regime. However, complete restoration of historic ecological conditions may be unrealistic given the consequences of past anthropogenic disturbances and human-induced climate change. Thus rather than aiming to fully restore past conditions, land managers should take an adaptive approach that strives to rehabilitate patterns and processes (*i.e.* frequent, low-severity fire), in a manner that takes into account the dynamic and unpredictable nature of forested ecosystems.

7.2 Future Research

Future research is needed to build upon the findings of this thesis. For example, a new study might use the network of fire-history sites now established for the Zuni Mountains and El Malpais National Monument (Grissino-Mayer 1995; Lewis 2003; this thesis) to conduct a synthesis of fire-climate relationships for northwestern, New Mexico. Although I compared the fire regimes of the Zuni Mountains to those of El Malpais National Monument, statistical analyses of the combined fire histories of both areas might yield interesting findings regarding climate-wildfire interactions at a broader spatial scale. Furthermore, the network of sites for the Zuni Mountains and El Malpais National Monument should be expanded. More sites both north and south of the study area would allow for a more spatially explicit examination of wildfire-climate relationships.

Additional research is also needed to examine the role of Native American burning in shaping wildfire regimes of the Zuni Mountains and the surrounding areas. Although it seems likely that prior to Euro-American settlement, lightning primarily ignited wildfires in the Southwest, this issue is still hotly debated (Denevan 1992; Kaye and Swetnam 1999; Krech 1999; Allen 2002; Barrett *et al.* 2005). Dendroecological studies that examines spatial differences in fire history relative to known Native American settlements might help clarify the effects that Native Americans did or did not have on pre-settlement fire regimes.

Finally, more understanding is needed of the anticipated effects of climate change on future wildfire regimes. Westerling *et al.* (2006) argued that western U.S. wildfire activity has increased due to warming temperatures and an earlier advent of spring, and suggested that future climate change will magnify these effects. The greatest increase in large wildfires in the West has occurred in forests of the Northern Rockies, an area relatively unaltered by anthropogenic disturbances. More research is needed to determine how human-induced climate change might alter wildfire regimes of the American Southwest, given the region's long history of livestock grazing, timber harvesting, and fire suppression.

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APPENDIX

Appendix 1 Years of fires that scarred at least 25% of all samples.

Year	Ratio of the number of scarred samples to the total number of recording samples	Percent scarred (%)
1700	8:12	66.7
1706	3:12	25.0
1709	5:12	41.7
1714	7:12	58.3
1719	3:11	27.3
1723	4:14	28.6
1724	8:17	47.1
1727	6:16	37.6
1729	9:18	50.0
1735	16:24	66.7
1748	24:30	80.0
1752	8:27	29.6
1755	13:25	52.0
1761	8:21	38.1
1763	15:30	50.0
1767	7:28	25.0
1773	32:39	82.1
1782	14:36	38.9
1789	22:44	50.5
1794	12:45	26.7
1795	12:45	26.7
1800	35:54	66.7

Appendix 1 *continued*

Year	Ratio of the number of scarred samples to the total number of recording samples	Percent scarred
1805	35:54	66.7
1810	17:50	34.0
1818	22:50	44.0
1819	15:46	33.0
1824	21:47	44.7
1826	14:46	30.4
1832	17:44	38.6
1841	31:49	63.3
1851	27:45	60.0
1859	18:45	40.0
1861	11:44	25.0
1870	23:43	53.5
1880	11:38	30.4

Appendix 2 COFECHA output summary statistics for series used in the Paxton Springs Cinder Cone tree-ring chronology.

	Series	Range of Years	# of Years	# of Segments	# of Flags	Corr. w/ Master	Mean Msmt	Max Msmt	Standard Deviation	Auto-correlation	Mean Sensitivity	Max Value	Standard Deviation	Auto-correlation	AR
1	PCC101A	1717–2008	292	12	0	0.772	0.59	1.86	0.307	0.443	0.484	2.81	0.422	-0.021	2
2	PCC101B	1753–2008	256	10	0	0.722	0.46	1.06	0.208	0.436	0.443	2.54	0.324	-0.019	1
3	PCC102A	1749–2008	260	11	0	0.813	0.86	2.91	0.447	0.571	0.44	2.5	0.327	-0.017	1
4	PCC102B	1713–2007	295	12	0	0.758	0.68	2.15	0.352	0.519	0.464	2.66	0.39	-0.039	1
5	PCC104B	1769–2008	240	10	0	0.762	1.08	2.97	0.61	0.695	0.384	2.63	0.459	-0.034	1
6	PCC105B	1666–2008	343	14	1	0.755	0.85	2.62	0.509	0.597	0.499	2.48	0.287	-0.021	1
7	PCC106A	1817–2008	192	8	0	0.742	0.8	2.98	0.56	0.633	0.564	2.5	0.358	-0.051	1
8	PCC109A	1848–2008	161	7	0	0.762	0.71	2.61	0.407	0.586	0.458	2.69	0.506	-0.036	1
9	PCC109B	1914–2008	95	4	0	0.796	1.31	3.47	0.79	0.685	0.428	2.63	0.587	-0.007	1
10	PCC111A	1831–2008	178	7	0	0.838	0.64	1.96	0.358	0.534	0.449	2.55	0.444	-0.038	1
11	PCC111B	1790–2008	219	9	2	0.739	0.98	2.27	0.411	0.243	0.451	2.65	0.443	-0.008	1
12	PCC112A	1721–2008	288	12	0	0.803	0.53	1.65	0.3	0.521	0.484	2.48	0.31	-0.037	1
13	PCC112B	1800–2008	209	8	0	0.713	0.47	1.01	0.221	0.442	0.463	2.55	0.388	-0.023	1
14	PCC113A	1740–2008	269	11	0	0.735	0.67	2.19	0.385	0.733	0.353	2.52	0.398	-0.018	1
15	PCC113B	1744–2008	265	11	0	0.789	0.89	2.59	0.538	0.773	0.318	2.6	0.396	-0.027	1
16	PCC114A	1746–1960	215	9	0	0.781	0.96	4.07	0.797	0.779	0.459	2.81	0.426	-0.044	1
17	PCC114B	1741–2008	268	11	0	0.829	0.81	3.17	0.552	0.679	0.45	2.64	0.392	-0.02	2
18	PCC115A	1750–2008	259	10	0	0.745	0.9	2.76	0.484	0.591	0.441	2.53	0.327	-0.035	3
19	PCC115B	1737–2008	272	11	0	0.779	0.8	3.02	0.428	0.613	0.43	2.63	0.426	-0.04	2
20	PCC116A	1882–2008	127	5	0	0.798	1.11	3.11	0.537	0.521	0.435	2.59	0.466	-0.032	1
21	PCC116B	1882–2008	127	5	0	0.653	1.08	4.22	0.737	0.695	0.467	2.84	0.452	-0.089	1
22	PCC117B	1906–2008	103	4	0	0.859	1.19	2.74	0.51	0.465	0.401	2.41	0.418	-0.035	1
23	PCC119A	1675–2000	326	13	1	0.614	0.63	5.08	0.505	0.817	0.402	2.48	0.318	-0.037	1
24	PCC119C	1649–2008	360	14	1	0.691	0.55	1.63	0.289	0.638	0.383	2.52	0.392	-0.049	1
25	PCC123B	1734–2008	275	11	0	0.761	0.58	1.46	0.284	0.486	0.419	2.46	0.284	-0.012	1
26	PCC124A	1829–2008	180	7	0	0.791	0.47	1.16	0.226	0.542	0.465	2.56	0.414	-0.032	1
27	PCC124B	1766–2008	243	10	0	0.756	0.48	1.27	0.219	0.512	0.396	2.5	0.334	0.018	1
28	PCC125A	1796–2008	213	9	0	0.735	1.14	2.77	0.539	0.537	0.419	2.56	0.422	-0.035	1
29	PCC125B	1810–2008	199	8	0	0.75	0.58	1.5	0.303	0.563	0.434	2.49	0.343	-0.014	1
30	PCC132A	1883–2008	126	5	0	0.794	1.79	5.83	1.036	0.741	0.391	2.55	0.398	-0.012	1
31	PCC132B	1852–2008	157	6	0	0.629	1.15	6.59	0.864	0.726	0.454	2.66	0.341	-0.027	1
32	PCC132C	1860–2008	149	6	0	0.828	1.82	3.74	0.81	0.679	0.335	2.53	0.387	-0.046	1
33	PCC133A	1874–2008	135	6	0	0.791	1.02	2.51	0.58	0.609	0.465	2.52	0.44	-0.003	1

Appendix 2 *continued*

	Series	Range of Years	# of Years	# of Segments	# of Flags	Corr. w/ Master	Mean Msmt	Max Msmt	Standard Deviation	Auto-correlation	Mean Sensitivity	Max Value	Standard Deviation	Auto-correlation	AR
34	PCC133B	1889–2008	120	5	0	0.804	1.02	3.56	0.705	0.64	0.524	2.68	0.529	-0.015	1
35	PCC135A	1888–2008	121	5	0	0.757	1.6	4.43	0.749	0.589	0.36	2.5	0.478	-0.061	2
36	PCC135B	1888–2008	121	5	0	0.763	1.15	3.83	0.639	0.707	0.379	2.53	0.425	-0.042	2
37	PCC136A	1886–2008	123	5	0	0.807	1.14	2.63	0.474	0.615	0.33	2.49	0.322	-0.002	1
38	PCC136B	1886–2008	123	5	0	0.804	1.15	3.68	0.525	0.584	0.331	2.58	0.336	0.003	1
39	PCC137B	1700–1999	300	11	0	0.813	0.72	2.31	0.391	0.505	0.464	2.41	0.284	-0.009	1
40	PCC137C	1731–2008	278	11	0	0.748	0.76	2.46	0.49	0.69	0.48	2.66	0.456	-0.068	1
41	PCC138A	1889–2008	120	5	0	0.808	1.9	5.49	0.964	0.561	0.446	2.42	0.334	-0.02	1
42	PCC139A	1870–2008	139	6	0	0.77	1.12	3.75	0.66	0.548	0.483	2.66	0.442	0.028	1
43	PCC139B	1870–2008	139	6	0	0.764	1.03	3.17	0.6	0.527	0.52	2.66	0.444	0.044	2
44	PCC140A	1870–2008	139	6	0	0.838	1.44	3.54	0.692	0.362	0.464	2.53	0.364	0.009	1
45	PCC140B	1891–2008	118	5	0	0.863	1.52	4.61	0.852	0.601	0.481	2.45	0.379	-0.018	1
46	PCC141A	1896–2008	113	5	0	0.788	1.27	3.21	0.619	0.595	0.42	2.48	0.416	-0.008	1
47	PCC145A	1817–2008	192	8	0	0.812	0.7	1.94	0.401	0.549	0.537	2.49	0.334	-0.02	1
48	PCC145B	1751–2008	258	10	0	0.806	0.67	2.03	0.349	0.501	0.495	2.6	0.374	-0.032	1
49	PCC146A	1707–2008	302	12	0	0.806	0.51	1.53	0.259	0.39	0.491	2.63	0.344	-0.039	1
50	PCC146B	1749–2008	260	11	0	0.792	0.52	1.44	0.269	0.429	0.472	2.78	0.376	-0.049	1
51	PCC151A	1945–2008	64	3	0	0.54	3.03	6.17	1.212	0.631	0.285	2.7	0.498	-0.087	2
52	PCC151B	1949–2008	60	3	0	0.63	2.97	9.72	1.734	0.8	0.257	2.57	0.399	0.028	1
53	PCC152A	1911–2008	98	4	0	0.748	2.28	7.68	1.474	0.798	0.312	2.43	0.373	-0.049	2
54	PCC152B	1903–2008	106	4	0	0.834	1.73	3.54	0.659	0.603	0.273	2.51	0.415	-0.004	2
55	PCC153A	1909–2008	100	4	0	0.852	1.83	5.86	1.261	0.881	0.328	2.52	0.396	-0.024	1
56	PCC153B	1900–2008	109	4	0	0.838	1.9	5.97	1.289	0.834	0.348	2.51	0.379	-0.03	1
57	PCC154A	1829–2008	180	7	0	0.784	1	2.38	0.504	0.614	0.467	2.6	0.516	-0.018	1
58	PCC154B	1837–2008	172	7	0	0.829	0.92	1.99	0.402	0.492	0.421	2.51	0.459	0.013	1
59	PCC155A	1794–2008	215	9	0	0.765	0.82	2.07	0.446	0.658	0.465	2.65	0.45	-0.009	1
60	PCC155B	1798–2008	211	9	0	0.737	0.83	4.51	0.532	0.626	0.492	2.77	0.455	-0.026	1
61	PCC156B	1903–2000	98	4	0	0.692	1.35	3.18	0.693	0.787	0.321	2.44	0.374	0.053	1
62	PCC157A	1824–2008	185	8	0	0.638	1.39	3.51	0.788	0.759	0.336	2.8	0.549	0.042	2
63	PCC157B	1900–2008	109	4	0	0.725	1.14	2.84	0.574	0.704	0.342	2.48	0.386	-0.032	1
64	PCC158A	1919–2008	90	4	0	0.666	1.56	2.99	0.532	0.503	0.299	2.75	0.492	-0.013	2
65	PCC158B	1909–2008	100	4	0	0.771	1.33	3.03	0.504	0.461	0.338	2.56	0.505	0.029	1

Appendix 2 *continued*

	Series	Range of Years	Total # of Years	# of Segments	# of Flags	Corr. w/ Master	Mean Msmt	Max Msmt	Standard Deviation	Series Auto-correlation	Mean Sensitivity	Max Value	Standard Deviation	Auto-correlation	AR
66	PCC159A	1837–2008	172	7	0	0.766	1.15	2.71	0.523	0.7	0.333	2.57	0.415	-0.033	1
67	PCC159B	1816–2000	185	8	0	0.604	0.9	1.97	0.434	0.627	0.335	2.45	0.323	-0.046	1
68	PCC160A	1874–2008	135	6	0	0.717	1.61	8.22	1.446	0.896	0.368	2.55	0.441	-0.01	2
69	PCC160B	1865–2008	144	6	0	0.747	1.51	4.54	1.104	0.871	0.398	2.51	0.464	-0.028	1
70	PCC160C	1862–2008	147	6	0	0.743	1.6	4.06	1.057	0.825	0.436	2.41	0.392	0.001	1
71	PCC161B	1878–2008	131	5	0	0.787	1.22	2.78	0.535	0.585	0.384	2.45	0.396	0.005	1
72	PCC162A	1858–1990	133	5	0	0.75	1.61	3.97	0.746	0.705	0.261	2.57	0.367	-0.011	1
73	PCC162B	1866–2008	143	6	0	0.768	1.16	3.54	0.753	0.788	0.377	2.62	0.439	0.031	1
74	PCC163A	1818–2008	191	8	0	0.834	0.65	1.3	0.286	0.317	0.488	2.45	0.412	-0.037	1
75	PCC163B	1778–2008	231	9	0	0.874	0.58	1.44	0.278	0.466	0.477	2.56	0.364	-0.024	1
76	PCC164A	1816–2008	193	8	0	0.775	0.74	2.26	0.388	0.628	0.416	2.54	0.361	-0.005	1
77	PCC164B	1828–2008	181	7	0	0.815	0.84	2	0.406	0.691	0.375	2.45	0.372	-0.011	1
78	PCC165A	1845–2008	164	7	0	0.646	0.65	3.2	0.54	0.749	0.556	2.53	0.407	-0.027	2
79	PCC165B	1781–2008	228	9	0	0.709	0.94	2.7	0.672	0.813	0.417	2.48	0.368	-0.043	1
80	PCC165D	1781–2008	228	9	0	0.558	0.94	2.91	0.657	0.736	0.471	2.51	0.331	-0.019	3

Appendix 3 Information on the periods of reliability used for sites in El Malpais National Monument. Modified from Grissino-Mayer (1995).

Site Name	Begin	End	Length (yrs)
Cerro Bandera East	1653	1880	228
Cerro Rendija	1684	1880	197
Lost Woman	1684	1861	178
Cerro Bandera North	1656	1880	225
La Marchanita	1625	1879	255
Candelaria	1703	1870	168
Hoya de Cibola	1653	1877	225
Mesita Blanca	1658	1933	276
Hidden Kipuka	1695	1935	241

VITA

Monica Rother grew up in both North Central Florida and in the Willamette Valley region of northwestern Oregon. Her love of the outdoors was inherited from her father, Chris Rother, a man of the woods. Monica pursued her undergraduate degree at Willamette University and was awarded a Bachelor of Arts in Environmental Science and Spanish in 2005. After graduation, Monica spent three years teaching middle school math and science in Oakland, California. She then joined the Geography Department at the University of Tennessee and began working towards a Master of Science degree as a member of the Laboratory of Tree-Ring Science. In Fall 2010, Monica will begin her dissertation work in the Geography Department at CU-Boulder as a member of its Biogeography Lab.